

"INVESTIGATION INTO THE NATURE
OF EMULSIFIED ASPHALTS COMPATIBLE
WITH CALIFORNIA LOCAL AGGREGATES
AND SUBSTITUTION OF SULFUR FOR
ASPHALT IN AQUEOUS
EMULSIFIED SYSTEMS"

FINAL REPORT



**WESTERN
TECHNOLOGIES,
INC.**

Phoenix

3737 East Broadway Road
P.O. Box 21387
Phoenix, Arizona 85036
(602) 268-1381

Flagstaff

2400 East Huntington Drive
Flagstaff, Arizona 86001
(602) 774-8708

Tucson

423 South Olsen Avenue
Tucson, Arizona 85719
(602) 624-8894

Farmington

400 South Lorena
Farmington, New Mexico 87401
(505) 327-4966

Las Vegas

300 West Boston Avenue
Las Vegas, Nevada 89102
(702) 382-7483

Grand Junction

P.O. Box 177
3224 Highway 6 & 24, No. 3
Clifton, Colorado 81520
(303) 434-9873

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BY

J. C. ROSNER, J. G. CHEHOVITS

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WESTERN TECHNOLOGIES, INC.
3737 EAST BROADWAY ROAD
PHOENIX, ARIZONA 85040

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Project Personnel

Joseph A. Pantalone	-	Contract Manager, Air Resources Board
Dr. John C. Rosner	-	Principal Investigator Western Technologies, Inc.
James G. Chehovits	-	Secondary Investigator, Western Technologies, Inc.

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ABSTRACT

This study investigated the use of solvent free asphalt emulsions and emulsions containing sulfur-extended-asphalt (SEA) as a base stock with low and high quality aggregates from California with the intent of substituting these emulsions for conventional emulsions and cutback asphalts in road construction. Emulsions studied included both cationic slow set and cationic medium set solvent free emulsions, a conventional cationic medium set emulsion which contained 7 percent solvent, and anionic slow setting SEA emulsions with both 15 and 30 percent sulfur-extended-asphalt-base stocks. Aggregates included a high quality crushed granite, a low quality pit run decomposed granite, and a low quality bank run gravel. Each aggregate was processed into a low and high quality level by addition of fines or partial washing.

Two statistically designed experiments were conducted to compare characteristics of paving mixtures containing the solvent free and SEA emulsions to those of the traditional emulsion. Aggregate and emulsion characteristics were determined. Emulsion-aggregate mixture characteristics including coating, stabilometer values, cohesiometer values, resilient modulus, air voids, voids in mineral aggregate, swell, moisture vapor susceptibility and surface abrasion were evaluated. Pavement section designs were performed for the mixtures to permit initial economic comparisons.

The study concluded that the solvent free asphalt and SEA emulsions studied could effectively coat and mix with all aggregates studied and that coatings were better than attained with the conventional emulsion. Stabilometer values in excess of 30 (minimum for Caltrans Type C asphalt concrete) were attained with many of the low quality aggregates with both the solvent free asphalt and SEA emulsions. Mixtures containing the solvent free cationic medium set emulsion were detrimentally affected by water to a greater degree than mixtures with the conventional solvent containing cationic medium set or solvent free cationic slow set emulsions. Mixtures made with the SEA emulsions were detrimentally affected by water to a high degree. Pavement structural designs showed that lesser pavement thicknesses are required when using solvent free or SEA emulsions as compared to conventional emulsions containing solvent. Recommendations are forwarded for additional laboratory work to compare mixture properties with both cutback and hot-mixed asphalts. Field test sections are also recommended.

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Glossary of Abbreviations

ANOVA	=	Analysis of variance
SBH	=	San Bernardino, high quality aggregate
SBL	=	San Bernardino, low quality aggregate
FH	=	Fresno, high quality aggregate
FL	=	Fresno, low quality aggregate
GRH	=	Graniterock, high quality aggregate
GRL	=	Graniterock, low quality aggregate
CSS-0	=	Cationic slow set solvent free emulsion
CMS-0	=	Cationic medium set solvent free emulsion
CMS-7	=	Cationic medium set emulsion coating, 7 percent solvent
SS-15	=	Anionic slow set sulfur extended asphalt at a 15 percent sulfur replacment
SS-30	=	Anionic slow set sulfur extended asphalt at a 30 percent sulfur replacement
SEA	=	Sulfur-extended-asphalt
TWT	=	Too weak to test

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B45	Mixture Design Data, Fresno, High Quality, SS-15% SEA, Replication 1	B45
B46	Mixture Design Data, Fresno, High Quality, SS-15% SEA, Replication 2	B46
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B48	Mixture Design Data, Fresno, High Quality, SS-30% SEA, Replication 2	B48
B49	Mixture Design Data, Fresno, Low Quality, SS-15% SEA, Replication 1	B49
B50	Mixture Design Data, Fresno, Low Quality, SS-15% SEA, Replication 2	B50
B51	Mixture Design Data, Fresno, Low Quality, SS-30% SEA, Replication 1	B51
B52	Mixture Design Data, Fresno, Low Quality, SS-30% SEA, Replication 2	B52
B53	Mixture Design Data, Graniterock, High Quality, SS-15% SEA, Replication 1	B53
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B55	Mixture Design Data, Graniterock, High Quality, SS-30% SEA, Replication 1	B55

B56	Mixture Design Data, Graniterock, High Quality, SS-30% SEA, Replication 2	B56
B57	Mixture Design Data, Graniterock, Low Quality, SS-15% SEA, Replication 1	B57
B58	Mixture Design Data, Graniterock, Low Quality, SS-15% SEA, Replication 2	B58
B59	Mixture Design Data, Graniterock, Low Quality, SS-30% SEA, Replication 1	B59
B60	Mixture Design Data, Graniterock, Low Quality, SS-30% SEA, Replication 2	B60
C1	Aggregate Coating At Design Residue Content, %	C1
C2	ANOVA Summary, Aggregate Coating	C1
C3	Film Stripping, %	C3
C4	ANOVA Summary, Film Stripping	C3
C5	2 Day Resilient Modulus at Design Residue Content, 10^3 psi	C5
C6	ANOVA Summary, 2 Day Modulus	C5
C7	Full Cure Resilient Modulus At Design Residue Content, 10^3 psi	C7
C8	ANOVA Summary, Full Cure Resilient Modulus ..	C7
C9	Density At Design Residue Content, pcf	C9
C10	ANOVA Summary, Density	C9
C11	Air Voids At Design Residue Content, %	C11
C12	ANOVA Summary, Air Voids	C11
C13	Stabilometer Value At Design Residue Content.	C13
C14	ANOVA Summary, Stabilometer Value	C13
C15	Cohesiometer Value At Design Residue Content.	C15

C16	ANOVA Summary, Cohesimeter Value	C15
C17	Swell At Design Residue Content, in.	C17
C18	ANOVA Summary, Swell	C17
C19	MVS Conditioned Stabilometer Value At Design Residue Content	C19
C20	ANOVA Summary, MVS Conditioned Stabilometer Value	C19
C21	MVS Conditioned Cohesimeter Value At Design Residue Content	C21
C22	ANOVA Summary, MVS Conditioned Cohesimeter Value	C21
C23	Surface Abrasion At Design Residue Content, grams	C23
C24	ANOVA Summary, Surface Abrasion	C23
D1	Aggregate Coating At Design Residue Content, %	D1
D2	ANOVA Summary, Aggregate Coating	D1
D3	Film Stripping, %	D3
D4	ANOVA Summary, Film Stripping	D3
D5	2 Day Resilient Modulus at Design Residue Content, 10^3 psi	D5
D6	ANOVA Summary, 2 Day Modulus	D5
D7	Full Cure Resilient Modulus At Design Residue Content, 10^3 psi	D7
D8	ANOVA Summary, Full Cure Resilient Modulus ..	D7
D9	Density At Design Residue Content, pcf	D9
D10	ANOVA Summary, Density	D9
D11	Air Voids At Design Residue Content, %	D11

D12	ANOVA Summary, Air Voids	D11
D13	Stabilometer Value At Design Residue Content.	D13
D14	ANOVA Summary, Stabilometer Value	D13
D15	Cohesimeter Value At Design Residue Content.	D15
D16	ANOVA Summary, Cohesimeter Value	D15
D17	Swell At Design Residue Content, in.	D17
D18	ANOVA Summary, Swell	D17
D19	MVS Conditioned Stabilometer Value At Design Residue Content	D19
D20	ANOVA Summary, MVS Conditioned Stabilometer Value	D19
D21	MVS Conditioned Cohesimeter Value At Design Residue Content	D21
D22	ANOVA Summary, MVS Conditioned Cohesimeter Value	D21
D23	Surface Abrasion At Design Residue Content, grams	D23
E1	Thickness T_i , in Inches to Satisfy Tensile Strain Requirements (Reference 3) ...	E1
E2	Thickness, T_s , in Inches to Satisfy Subgrade Strain Requirements (Reference 3)	E2
E3	Thickness Requirements, inches; $E_s = 6000$ psi, $EAL = 1 \times 10^4$, MAAT = 55-65F	E8
E4	Thickness Requirements, inches; $E_s = 6000$ psi, $EAL = 1 \times 10^5$, MAAT = 55-65F	E9
E5	Thickness Requirements, inches; $E_s = 6000$ psi, $EAL = 1 \times 10^4$, MAAT $> 65F$	E10

E6	Thickness Requirements, inches; E _s = 6000 psi, EAL = 1 x 10 ⁵ , MAAT > 65F	E11
E7	Thickness Requirements, inches; E _s = 30,000 psi, EAL = 1 x 10 ⁴ , MAAT = 55-65F	E12
E8	Thickness Requirements, inches; E _s = 30,000 psi, EAL = 1 x 10 ⁵ , MAAT = 55-65F	E13
E9	Thickness Requirements, inches; E _s = 30,000 psi, EAL = 1 x 10 ⁴ , MAAT > 65F	E14
E10	Thickness Requirements, inches; E _s = 30,000 psi, EAL = 1 x 10 ⁵ , MAAT > 65F	E15

1.0 INTRODUCTION

1.1 Background

Bituminous binders used in pavement construction may be classified into three groupings - asphalt cements, cutback asphalts, and emulsified asphalts. Asphalt cements are generally produced as an end product from the refining of crude oil and are semi-solids at ambient temperature. In order to use asphalt cements in pavement construction, both the aggregate and asphalt cement are heated to between 250 and 325F.* At these temperatures, asphalt cement is relatively fluid and will effectively coat the aggregate when mixed. Mixing is generally accomplished in a central or portable plant. While the mixture is hot, 250 to 325F, it may be spread on a prepared base, and then compacted to form a durable pavement surface. The asphalt cement-aggregate mixture (hot-mixed asphalt concrete) gains strength as it cools to ambient temperature.

During production of hot-mixed asphalt concrete much energy is consumed while heating the asphalt cement and aggregate. In remote areas, and for rather small projects, the requirement of using the central or portable mixing plant may be restrictive. In remote areas, many times, either cutback or emulsified asphalts are used instead of asphalt cements. Cutback asphalt is an asphalt cement which has been liquified by blending with various types of petroleum based solvents. Emulsified asphalts are fluid dispersions of asphalt in water. Both cutback and emulsified asphalts are fluid at ambient temperatures and may readily be mixed with aggregates at ambient temperatures thus offering a potential energy savings when compared to hot-mixed asphalt concrete. The mixtures may be placed and compacted to form a pavement.

Cutback and emulsified asphalts gain strength by evaporation of the fluidizing medium. With cutbacks, petroleum based solvents are evolved and with emulsions, water. It has been estimated that approximately 25,000 tons of solvents are evolved into the atmosphere each year in California from cutback asphalts (1).** This not only is a major source of hydrocarbon emissions, but is a waste of a non-renewable resource.

Notes:

* All temperatures cited herein are in terms of degrees.

** Numbers in parenthesis indicate references at end of text.

Addition of solvent to asphalt emulsions has been found to improve the coating ability of the emulsion when used with poor or marginal quality aggregates. Traditional asphalt emulsion formulations may contain up to 12 percent solvent (2). The substitution of traditional emulsified asphalts for cutbacks may reduce hydrocarbon emissions, but the reduction may not be large due to the presence of solvents in the emulsified system. Additionally, use of solvents in emulsions tend to soften the asphalt residue which may result in poorer field performance.

Recently, asphalt emulsions have been developed which can effectively coat marginal or poor quality aggregates without the use of petroleum based solvents. Use of solvent free asphalt emulsions in place of cutback asphalts has been estimated to have the potential of reducing hydrocarbon emissions by approximately 22,000 tons per year in California, an 85 percent reduction (1).

Traditional emulsified asphalts, however, have been found to perform poorly and not be compatible with low quality aggregates, especially aggregate which contain a high amount (greater than 15 to 20 percent) of claylike fines (3). Since aggregates which are locally available for road construction in several sections of California typically may contain high amounts of claylike fines, use of asphalt emulsions with these types of aggregates has not been extensive in California.

Recently considerable research has been performed with the use of sulfur as a partial substitute for asphalt in hot-mix paving applications. Sulfur has been used to extend asphalt cement by as much as 50 percent by weight (4). Paving mixtures containing these sulfur-extended-asphalts (SEA) have been found to have many properties comparable to those of conventional hot-mixed asphalt concretes. However, a major problem which exists when using SEA in paving is that if mixture temperatures exceed approximately 300F, sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) gases can be evolved creating possible health and environmental hazards (5). Use of a water based emulsified SEA binder would permit mixing and compacting of paving mixtures at ambient temperatures thus lessening environmental hazards and increasing the attractiveness of using sulfur as a partial replacement for asphalt.

1.2 Project Objectives

Objectives of this research project are twofold. First, this study investigates the feasibility of using solvent free emulsified asphalts with local, low quality aggregates in California. The second objective is to investigate the feasibility of using water-based sulfur-extended-asphalt emulsions with low quality California local aggregates.

1.3 Project Scope

The study investigated the use of both cationic medium set (CMS) and cationic slow set (CSS) solvent free asphalt emulsions. For comparison purposes, a conventional CMS asphalt emulsion which contains 7 percent solvent is studied. The solvent used was pure distilled reagent grade naptha produced by Varnish Makers and Painters.

Aggregates studied are from three different California sources, one, a high quality crushed granite, the second, a low quality bank run material, and the third, a low quality pit run material. Each of the three aggregates was processed into a high and low quality level by partial washing or addition of fines. Thus, a total of 6 aggregate combinations which are representative of many aggregates available in California for pavement construction were studied.

Two sulfur-extended-asphalt emulsions were studied during the second portion of the investigation. These were anionic slow set (SS) emulsions formulated with both a 15 percent SEA binder and a 30 percent SEA binder. Properties of mixtures containing these two emulsions were also studied with the 6 different project aggregates.

1.4 Investigational Procedure

Two statistically designed experiments were conducted to compare characteristics of paving mixtures containing the solvent free and SEA emulsions to those of the traditional emulsion. Aggregate and emulsion characteristics were determined. Emulsion-aggregate mixture characteristics including coating, stabilometer values, cohesiometer values, resilient modulus, air voids, voids in mineral aggregate, swell, moisture vapor susceptibility and surface abrasion were investigated. Pavement section designs were performed for the mixtures to permit initial economic comparisons.

2.0 LITERATURE REVIEW

2.1 Emulsified Asphalts

Background. Emulsified paving asphalts consist of fine droplets of paving grade asphalt which are suspended in water by surface active emulsification chemicals. Typical asphalt droplet diameter in emulsions is between 0.25 and 10 microns (6). Emulsified asphalts are liquid at ambient temperatures enabling handling, pumping, spraying, and mixing with aggregate with little or no heating.

Asphalt emulsions were developed and used in road construction in the 1920's (6). The major early use of emulsified asphalts was as surface treatments for roadways and as a dust palliative. During the past decade, interest in use of asphalt emulsions has been becoming increasingly more attractive in all phases of flexible pavement construction and maintenance. Factors prompting this increased interest are both energy and environment related. The fact that emulsions can be mixed with aggregate and applied to pavements with little or no heating is attractive due to the energy savings afforded as compared to use of asphalt cements which required heating of materials. In comparison to cutback asphalts which contain petroleum based solvents as a fluidizing medium, asphalt emulsions are fluidized by water. Thus, substitution of emulsified asphalts for cutbacks can result in lessened consumption of petroleum based solvents. Since emulsified asphalts harden as a result of water evaporation, substitution of emulsified asphalts for cutbacks also results in lessened atmospheric pollution (7). Another factor which is responsible for the increasing use of emulsified asphalts is the development of more types of emulsions, especially cationics, which permit successful use in a wider range of applications than with anionics.

From 1970 to 1980, sales of cutback asphalts in the United States have dropped from approximately 4 million to 1.8 million tons per year. Sales of emulsified asphalts during the same period have increased from 2.5 to 3.2 million tons per year (8).

Currently, major uses of emulsified asphalts in highway applications are in soil and low quality aggregate stabilization, dust palliation, base course construction, seal coats, fog seals, and slurry seals (3, 6, 9, 10, 11). Emulsions have not been used extensively as binders for quality asphalt concrete construction, although use in this function is increasing. Several states including New York, Pennsylvania, and Illinois routinely use emulsified asphalts as cold-mix binders (7).

Asphalt Emulsion Basics. An asphalt emulsion may be defined as a heterogeneous system containing at least one immiscible liquid intimately dispersed in another in the form of droplets whose diameter in general exceeds 0.1 microns (11). Such systems possess a minimal stability, which may be accentuated by additives such as surface active agents and finely divided solids (12).

Asphalt emulsions are manufactured by pumping both molten asphalt and water into a high speed colloid mill, homogenizer, or ultrasonic emulsator (12). Appropriate emulsifying chemicals are premixed in the water phase to form what is referred to as the soap solution. The type and concentration of emulsifying chemical used influences several characteristics of the emulsion such as asphalt droplet surface charge, rate of setting when used, and storage stability or settlement properties. Two basic types of emulsions which are classified with respect to asphalt droplet surface charge are used in paving - anionic and cationic. With anionic emulsions, the emulsification chemical imparts a negative surface charge to the asphalt droplet. Cationic asphalt emulsifiers impart a positive surface charge to the asphalt droplets.

Common anionic emulsifying chemicals include soaps of sodium, potassium and amines (12). Common cationic emulsification chemicals are tabulated in Table 1. Emulsifier chemical type and concentration can influence the setting rate of emulsions (the rate at which the asphalt in the emulsion breaks out of the emulsion and coats the aggregate surface). Three setting rate classifications are available - slow setting (SS), medium setting (MS), or rapid setting (RS) for anionic emulsions. For cationic emulsions, the same setting rates are available, but the designations are preceded by a C to indicate

Table 1

CATIONIC EMULSIFYING CHEMICALS (Reference 12)

n-Lauryl ammonium chloride
n-Palmityl ammonium chloride
n-Octadecyl ammonium chloride
Cocoyl ammonium chloride
Stearyl ammonium chloride
Dicocoyl ammonium chloride
Di-H-tallow ammonium chloride
Alkyl trimethyl ammonium chloride
Cocoyl ammonium acetate
Stearyl ammonium acetate
Tallow ammonium acetate
n-Octyl ammonium acetate
n-Dicyl ammonium acetate
n-Lauryl ammonium acetate
n-Octadecyl ammonium acetate
n-Palmityl ammonium acetate
Cetyl trimethyl ammonium bromide

cationic characteristics. Emulsions with slow setting characteristics have a higher degree of stability than rapid setting types. Increased stability is mainly accomplished through the use of different types and greater concentrations of emulsification chemicals. Emulsion having slow setting characteristics (higher degree of stability) permit mixing for longer times with finer aggregates and retard the tendency to break more than emulsions with medium or rapid setting characteristics.

Most construction aggregates generally carry a negative surface charge (13), the magnitude of which is determined by several factors indicating mineralogic composition, degree of weathering, and surface coatings. Since asphalt particles in cationic emulsions carry a positive surface charge, the asphalt phase is electro-chemically attracted to aggregate surfaces when mixed with aggregates. The degree of attraction depends on the magnitudes of surface charges of both the asphalt particles and aggregate surfaces. Asphalt droplets in cationic slow setting (CSS) emulsions have lower surface charges than those of CMS or CRS emulsions resulting in a lesser degree of attraction. The surface charge of asphalt droplets in emulsions may be indicated by the Zeta potential of the emulsion (13). Zeta potential of CRS emulsions is approximately +100 mv, that of CMS emulsions, +60 mv, and that of CSS emulsions, +30 mv.

The major mechanism of breaking for cationic emulsions is that of electro-chemical attraction between the aggregate surface and the asphalt droplets. For anionic emulsions, the negatively charged asphalt droplets are not strongly attracted to aggregate surfaces and the mechanism of break is that of water evaporation from the emulsion in sufficient amount such that the emulsion becomes instable and deposits asphalt droplets on aggregate surfaces (13).

Other characteristics of emulsions such as viscosity, stability and asphalt droplet size may be modified by addition of certain chemicals or other additives, or changes in production techniques (12).

Emulsified Asphalt Mix Performance. Many references are available in the literature on construction and performance of paving mixtures containing emulsified asphalts. Many of the references report on experimental projects and compare properties of emulsified

mixes to hot-mix or cutback asphalt mixes. Several references which consider emulsified asphalt paving mixtures for structural purposes (as opposed to seal coats, slurry seals, fog seals, etc.) are discussed in the following sections.

Beagle (14), in 1976, reported on the performance of a 5 inch thick emulsified asphalt base of a municipal street placed in New Jersey in 1963. Based on deflection measurements and field performance, it was concluded that the structural adequacy of the emulsified asphalt base course was equal to that of hot, plant-mixed asphalt concrete. It was noted that this project used the same dense-graded aggregate and binder contents with the emulsified and hot-mixed asphalt concretes. Also, the degree of compaction obtained in the emulsion-mix and the hot-mix were very similar (4.05% air voids for the emulsion mix and 4.2 for the hot-mix).

Meier (15) has summarized construction of emulsified asphalt pavements on the Navajo Reservation in Arizona and New Mexico. In this area, the Bureau of Indian Affairs has placed over 1,000,000 tons of emulsified asphalt paving mixtures. Roadways constructed are relatively low volume roads with typical cross sections being 10 to 12 inches of asphalt emulsion treated base with a 2 inch thick emulsified asphalt surface course. Emulsified asphalt base courses on the Reservation have been successfully constructed using sand aggregates with 23 to 27 percent minus No. 200 mesh (75 um) material and CSS-1h emulsions. The use of emulsified asphalt base instead of hot-mix was reported to result in a 33 percent cost savings over hot-mix for a particular project. Meier also states that specifications, design, and construction procedures when using emulsified asphalts require revisions to adapt to local materials, conditions and desires.

Construction and performance of the San Diego County Experimental Base Project has been reported by Kallas and Shook (16). Objectives of the project were to compare the performance of several types of pavement bases, to relate measured pavement properties of pavements and components to observed performances, and to study deflection behavior of pavements to attempt to predict performance. The study

included hot-mixed, emulsified, cutback, and untreated base courses constructed with several aggregate types. It is important to note that in this project, both cutback and emulsified asphalt were only used with medium to low quality aggregates, while the hot-mix base was constructed with high quality dense-graded aggregate and the medium quality aggregate. Gradations of the high, medium, and low quality aggregates as well as binder contents studied with the three binder types are shown in Table 2. From Table 2, it is noted that not only aggregate type, but also binder contents which were studied varied. Additionally, differences in the stiffnesses of binders varied as the asphalt cement used in hot-mixes was a 60-70 penetration material compared to the SM-K emulsion residue penetration specification of 100-250 (17).

Recommended layer equivalencies determined as a result of the study for base sections considered are tabulated in Table 3. From Table 3, it is noted that a 1.4 to 1.0 replacement is recommended for low to medium quality aggregate emulsion mixes when replacing high quality aggregate hot-mix. However, it is very interesting to note that when using the same medium quality aggregate, equivalencies for hot-mix asphalt cement, emulsified asphalt, and cutback asphalt, are all 1.4. These results indicate that when using the same quality aggregate, layer equivalencies for pavement section designs were the same for mixtures made with asphalt cement, cutback asphalt, and emulsified asphalt. It is also interesting to note that the layer equivalency of the emulsion treated low quality aggregate base is also 1.4.

Chevron (9) reports several case histories of construction projects using emulsified asphalt as a binder with a wide range of aggregates including low quality aggregates with high (greater than 10 percent) minus No. 200 mesh contents which are performing excellently after several years of service.

Wimberly (18) has reported on the successful use of emulsified asphalts with low quality aggregates as base and surface courses in several sections of Arizona.

Table 2

GRADATIONS AND SAND EQUIVALENTS,
OF AGGREGATES AND BINDER CONTENTS
STUDIED IN THE SAN DIEGO BASE PROJECT
(Reference 16)

<u>Sieve Size</u>	<u>%Passing</u>		
	<u>High</u>	<u>Medium</u>	<u>Low</u>
1" (25.4 mm)	100	100	100
3/4" (19.0 mm)	100	100	99
1/2" (12.5 mm)	92	99	97
3/8" (9.5 mm)	76	89	95
No. 4 (4.75 mm)	53	74	90
No. 8 (2.36 mm)	38	69	74
No. 16 (1.18 mm)	30	63	57
No. 30 (600 um)	23	52	43
No. 50 (300 um)	14	25	29
No. 100 (150 um)	7	15	20
No. 200 (75 um)	4.6	10	13
<hr/>			
Sand Equivalent	56	29	34
 Binder Contents; %			
Asphalt Cement (60-70) Pen.	5.8	5.8	-
Cutback (MC-800)	-	5.1	-
Emulsified (SM-K or CMS-2S)	-	4.2	3.1

Table 3

RECOMMENDED LAYER EQUIVALENCIES FROM
THE SAN DIEGO BASE PROJECT (Reference 16)

<u>Binder Type</u>	<u>Aggregate Quality</u>	<u>Equivalency</u>
Asphalt Cement	High	1.0
Asphalt Cement	Medium	1.4
Cutback Asphalt	Medium	1.4
Emulsion Treated	Medium	1.4
Emulsion Treated	Low	1.4

In summary, several references are available in the literature on the successful use of emulsified asphalts with both high and low quality aggregates. In several instances, comparisons between emulsified asphalt mixtures and hot-mix or cutback treated mixtures made with the same aggregate have indicated that performance was similar. It is also reported that specifications, designs and construction procedures need to be adapted to local conditions and materials when using emulsified asphalts.

2.2 Sulfur-Extended-Asphalts

Background. Due to rising costs and potential shortages of asphalt cement for the highway industry, much research directed at lessening the dependence of highway construction on asphalt cement has been undertaken. Major objectives of this research are to identify substitutes or extenders for asphalt cement and to develop required technology for their use. Sulfur has been identified as a substance which can be used as a partial or total replacement for asphalt cement in pavement construction. Attractiveness of using sulfur in paving is enhanced due to predicted future surpluses resulting from increased involuntary production (mainly desulfurizing operations such as for stack gases from coal burning power plants and sour crudes or natural gas).

Three different methods of using sulfur in asphalt paving have been identified. These methods are as a structuring agent in mixtures containing poorly graded sand and asphalt (sand-asphalt-sulfur mixture) (12, 20), as an extender for cements (sulfur-extended-asphalt) (4, 20), and as a total replacement for asphalt cement binders (plasticized sulfur or Sulphlex) (21). Use of sulfur-extended-asphalt in paving is nearing the state of common usage as many successful test sections have been placed. More research, both lab and field, however is required to determine the usefulness of plasticized sulfur materials. Characteristics and properties of sulfur-extended-asphalts are further discussed as their use was studied in this investigation.

Properties of Sulfur. Sulfur, the tenth most abundant element on earth, may exist in twelve different allotropic forms. However, only three forms are common - rhombic, monoclinic, and polymeric. Rhombic sulfur is the normal form of sulfur (pale yellow solid crystals) at ambient temperature and pressure. Rhombic sulfur is structured as an 8-atom ringed molecule. When the temperature of rhombic sulfur exceeds 235F, the sulfur melts to form a pale yellow liquid with a low viscosity (approximately 12 centipoises). Above 270F, the rings of sulfur begin to break and form chains composed of 8 sulfur atoms. Above 300F, the chains join forming a polymeric structure resulting in a rapid increase in viscosity. The temperature-viscosity relationships of sulfur are shown in Figure 1 along with those of 2 paving grade asphalts. Sulfur in the linked chain structure is in its polymeric form. If molten polymeric sulfur is cooled quickly, it retains its polymeric structure and forms a rubbery solid. However, if cooled slowly, monoclinic sulfur, a relatively hard solid is formed. Both monoclinic and polymeric sulfur have desirable characteristics useful in construction; however, these forms are not stable and at ambient temperature and pressure will revert back to rhombic sulfur within a relatively short time.

Sulfur-Extended-Asphalt. Sulfur-extended-asphalt (SEA) is a binder composed of asphalt cement and sulfur. The use of sulfur as an extender for asphalt cement results in the use of less asphalt to produce the same volume of binder. Sulfur extensions ranging from 10 to 50 percent by weight of the SEA have been studied (4) and used in field test sections. Physical properties of SEA vary according to the amounts of sulfur used and asphalt cement type. The specific gravity of SEA is greater than that of asphalt cement due to the higher specific gravities of sulfur (2.07) as compared to asphalt cement (1.00-1.03). It has been determined that up to approximately 19 percent sulfur by weight of the total SEA binder will dissolve in asphalt cement at temperatures between 250 and 300F. On cooling, the dissolved sulfur in SEA will not recrystallize to form solid sulfur but remains dissolved in the asphalt (21). If greater than 19 percent sulfur is present in the SEA, the sulfur in excess of 19 percent will be present in a dispersed state. Thus,

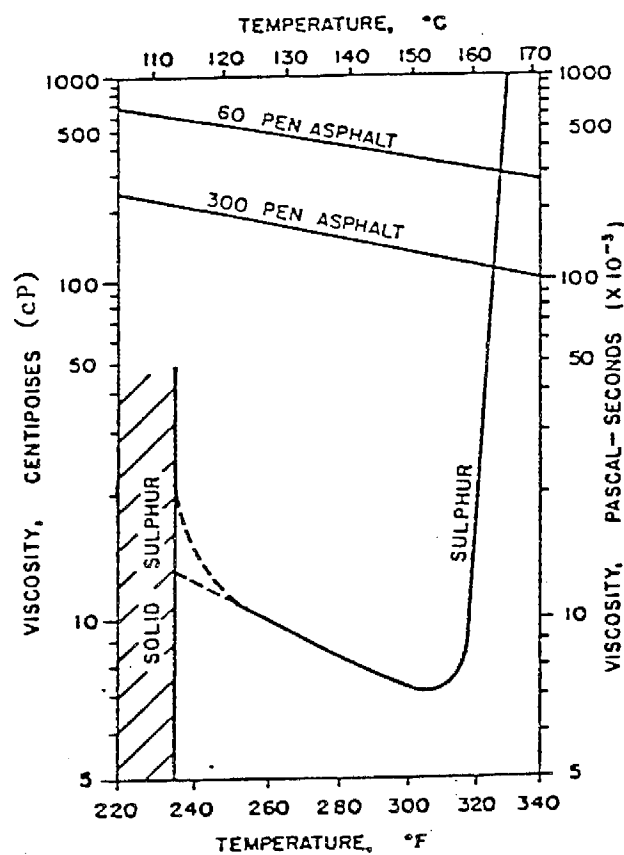


Figure 1. Temperature-Viscosity Relationships for Sulfur. (1 centipoise = 0.01 poise) (5).

two basic types of SEA exist - one with all dissolved sulfur (less than 19% sulfur), and one containing both dissolved and dispersed sulfur (greater than 19% sulfur). Depending on the blending process used in production of the SEA binder, the dispersed sulfur may exist as droplets or particles (depending on the temperature of the binder) which range in size from less than 5 microns to large particles which may function as a filler. Table 4 shows the 140F absolute viscosity and 280F Brookfield viscosity of several sulfur-extended-asphalts. From Table 4, it can be seen that the 140F and 280F viscosities of SEA vary according to the percentage of sulfur used. As little as 10 percent sulfur results in a much less viscous material when compared to the base asphalt cement while higher sulfur contents (especially over 40%) tend to increase viscosity. It has also been noted that increasing sulfur contents result in decreased ductilities and flash points (4).

Paving mixtures made with SEA generally exhibit characteristics which are comparable to conventional asphalt concretes. However, it has been reported that SEA binders may tend to age harden to a greater degree than asphalt cement (22). Moisture resistance characteristics are not agreed on. Both increased (4) and decreased (23) resistance to moisture damage have been noted.

When SEA binders are heated in excess of 300F, sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) gases may be evolved creating possible health and environmental hazards (5). This characteristic of SEA mixtures needs to be considered during construction of hot-mix SEA pavements.

Sulfur-Extended-Asphalt Emulsions. Recently, production and characteristics of water-based SEA emulsions were studied (24). Several anionic and cationic emulsions using SEA binders which contained between 10 and 40 percent sulfur were studied. The study concluded that it is possible to formulate and produce stable SEA emulsions which have many characteristics which, in many ways, are comparable to standard asphalt emulsions. It was also determined that emulsification characteristics of SEA binders with less than 19 percent sulfur were different than for SEA containing greater than 19 percent sulfur.

Table 4

VISCOSITIES OF SULFUR-EXTENDED-ASPHALT BINDERS
OF VARYING REPLACEMENT PERCENTAGES (4)

<u>Sample Description</u>	<u>Sulfur Content Percent Weight</u>	<u>Viscosities</u>	
		<u>140°F (60°C) ASTM D 2171 Poise</u>	<u>280°F (138°C) (Brookfield) C.S.</u>
85-100 pen asphalt	Nil	1557	318
S/A binder	10	570	205
S/A binder	20	691	145
S/A binder	30	772	153
S/A binder	40	950	148
S/A binder	45	1077	168
S/A binder	50	2494	380
S/A binder	60	5081	583

3.0 MATERIALS

3.1 Aggregates

Three different aggregate sources from California were used in mixtures studied during this investigation. A high quality crushed granite and two low quality local aggregates were studied. The high quality crushed granite was obtained from the Graniterock Quarry at Aromas, California. One low quality aggregate was a pit run material from San Bernardino County. The second is a bank run material from Fresno County. Sufficient material to complete the study was sampled from each source. Gradations, sand equivalents, and moisture contents of the aggregates as sampled are tabulated in Table 5.

San Bernardino. The San Bernardino aggregate was obtained from the Hesperia Landfill pit which is located approximately 30 miles north of San Bernardino, California. This aggregate source is frequently used with slow curing cutback asphalts for road construction, and is representative of low quality local aggregates used in San Bernardino County. During production of cutback asphalt mixtures, the aggregate is processed over 3/4 inch screens to remove oversize fractions.

Microscopic examination of the 1/2 inch to 3/4 inch fraction of the San Bernardino aggregate showed that it is composed of several types of materials all of which can be termed as granite gneiss and weathered granite. Minerals present in the aggregate include metaquartzite, quartz, sodic plagioclase, magnetite, biotite, microcline and potassium feldspars. The weathered granite particles are structured mainly as a coarse grained network of quartz particles cemented together by weathered sodic plagioclase resulting in an easily abraded particle. The sodic plagioclase appears to be weathering into clay minerals. The granite gneiss particles are composed mainly of potassium feldspar and quartz and are not weathered to the extent as the weathered granite particles. Particle shape of the 1/2 to 3/4 inch fraction is sub-angular to cubical with a coarse grained texture.

Table 5

GRADATIONS, SAND EQUIVALENT VALUE,
AND MOISTURE CONTENT OF
"AS SAMPLED" AGGREGATES

Sieve Size	% Passing				
	Graniterock			Crusher	
	Fresno ¹	1/2"	1/4"	Sand	San Bernardino ²
1" (25.0 mm)	100	100	100	100	100
3/4" (19.0 mm)	92	100	100	100	100
1/2" (12.5 mm)	82	99	100	100	96
3/8" (9.5 mm)	75	60	100	100	93
1/4" (6.3 mm)	67	10	88	100	89
#4 (4.75 mm)	62	9	48	100	86
#8 (2.36 mm)	51		9	88	77
#10 (2.00 mm)	49		7	81	72
#16 (1.18 mm)	46		5	64	60
#30 (600 um)	41		3	46	40
#40 (425 um)	37		3	39	32
#50 (300 um)	32		3	32	24
#100 (150 um)	20		2	23	16
#200 (75 um)	13.4		1.5	15.4	10.3
<hr/>					
Sand Equivalent	15	-	78	60	29
Moisture Content; %	6.7	0.5	2.2	0.4	1.8

Notes: ¹Material scalped on a 1" (25.0 mm) screen prior to sieve analysis.

²Material scalped on a 3/4" (19.0 mm) screen prior to sieve analysis.

The No. 16 to No. 30 mesh fraction of the San Bernardino aggregate is composed of approximately 60 percent quartz grains, 20 to 25 percent potassium feldspar grains and 15 to 20 percent weathered mica. Particle shape is mainly cubical and sub-angular.

The minus No. 100 mesh fraction of the aggregate contains a higher percentage of weather mica and quartz grains and less potassium feldspar than the No. 16 to No. 30 mesh fraction. Additionally, many clay and silt size particles are present as well as magnetite. Particle shape is mainly sub-angular.

The aggregate contains only a small amount of coarse (plus No. 4 mesh) material (14 percent) and has 10.3 percent finer than the No. 200 mesh sieve. The sand equivalent value of the aggregate is 29 (Table 5).

Fresno. The Fresno aggregate was obtained from the Cantua Creek pit which is located approximately 40 miles southwest of Fresno, California and 20 miles north of Coalinga. This aggregate source is commonly used with medium curing cutback asphalts for road construction and is representative of low quality aggregates used in Fresno County. During production of cutback asphalt mixtures, the aggregate is processed over 1 inch screens to remove oversize material.

Microscopic examination of the 1/2 inch to 1 inch fraction of the Fresno aggregate showed that it is composed of several very different types of particles. The particles range in hardness from relatively weak to hard and durable. Most of the particles are of metamorphic origin. Types of materials observed include a highly weathered gabbro or hornblende, weather serpentine, dense metagreywake, weathered greywake and weathered schist. Most particles contain dark siliceous mineral assemblages which include fine mica and magnetite particles. The serpentine and schist particles contain many microfractures along which fracture may easily occur on impact. Particle shape of this size fraction varies ranging from flattened to cubical particles, all of which are well rounded.

The No. 16 to 30 mesh fraction of the Fresno aggregate is composed of quartz grains (20 to 30 percent), various weathered feldspars, magnetite, schist, and many other fine particles of various

other mineral types. Many plate and rod shaped particles which are semi-rounded or oval in shape are present. A higher proportion of quartz is observed in the finer portion (No. 30 mesh) than in the coarser (No. 16 mesh).

The minus No. 100 mesh fraction of the material contains a large proportion of clay and silt-sized particles. In comparison to the No. 16 to No. 30 mesh fraction, more quartz particles (60 to 70 percent) are observed as well as less feldspar and various other mineral types.

The aggregate contains 38 percent coarse (plus No. 4 mesh) material and has 13.4 percent finer than the No. 200 mesh sieve. The sand equivalent value of the aggregate is 15 indicating a high amount of claylike fines (Table 5).

Graniterock. The Graniterock aggregate was obtained from the Graniterock Quarry at Aromas, California which is approximately 40 miles south of San Jose. This aggregate is typical of high quality aggregate used in California and is routinely used in production of hot-mixed asphalt concrete.

Microscopic examination of the 1/2 inch to 3/8 inch fraction showed that the aggregate is a medium-to-coarse-grained granite which exhibits a high degree of interlocking between grains. Minerals present in the aggregate include plagioclase, mica, hornblende, pyroxene and quartz. Particle shape varies from cubical to semi-elongated and is very angular.

The minus No. 50 mesh fraction of the aggregate contains a high percentage of quartz, mica, potassium feldspar, and plagioclase. Small amounts of serpentine, amphibole and magnetite are noted. Moistening of this fraction showed a very high affinity for water indicating a high surface charge. Particle shape varies between cubical to semi-elongated and is very angular.

Three different size fractions of the Graniterock aggregate were obtained. These fractions are designated as 1/2 inch, 1/4 inch, and crusher sand by the producer. Gradations of each fraction are tabulated in Table 5. The sand equivalent value of the crusher sand is 60 indicating that the fines are high quality crushed rock.

3.2 Aggregate Quality Levels

As stipulated in the project Request for Proposals (1), aggregates to be studied are to be those with sand equivalent values ranging from 20 to 30 and with minus No. 200 (75 μ m) mesh contents between 10 and 25 percent. In order to investigate not only the effects of aggregate type, but also the level of quality of each aggregate, each of the three aggregates being studied was processed into both a "high" and "low" quality level as indicated by sand equivalent value and minus No. 200 mesh content. For purposes of this study, high quality aggregates are defined as those with sand equivalent values of approximately 30 or above and with minus No. 200 mesh contents near 10 percent, while low quality materials have sand equivalents of approximately 20 and minus No. 200 mesh contents between 10 and 20 percent. Methods used to process each of the three aggregates into both high and low quality levels are discussed in following sections.

San Bernardino. The "as received" San Bernardino aggregate (after being scalped on the 3/4 inch screen) had a sand equivalent value of 29 and a minus No. 200 mesh content of 10.3 percent. Thus, the "as received" San Bernardino aggregate met criteria for the high quality level. The low quality level was achieved by adding 8.6 percent of powdered kaolinite clay obtained from Revlon, Inc. of Phoenix, Arizona. The kaolinite has an apparent specific gravity of 2.60 and is 100 percent finer than the No. 200 sieve.

Resulting sand equivalent value for the low quality level is 18 and the minus No. 200 mesh content is 17.4 percent. The high quality San Bernardino aggregate is typical of a relatively clean decomposed granite aggregate. The low quality level material is representative of a decomposed granite which contains a high amount of claylike fines.

Fresno. The "as received" Fresno aggregate (after being scalped on the 1 inch screen) had a sand equivalent value of 15 and 13.4 percent minus No. 200 mesh material. Thus, the "as received" Fresno aggregate was selected as the low quality material. The high quality level of the Fresno aggregate was achieved by washing the aggregate to partially remove fines. The washing technique used consisted of

placing the minus No. 4 mesh fraction in a trough and then flooding with water to float out a portion of the fine material. Following washing, the aggregate was dried in an oven and then thoroughly re-mixed to eliminate segregation which occurred during washing. The sand equivalent value of the washed minus No. 4 mesh fraction was found to be 29 which was near the high quality criteria. The washed minus No. 4 mesh fraction was combined with the coarse (No. 4 mesh to 1 inch fraction) to yield the high quality Fresno aggregate. The minus No. 200 mesh content of the Fresno high quality aggregate was 7.9 percent.

The high quality Fresno aggregate is representative of bank run gravel which contains a rather small portion of claylike fines. The low quality level is representative of a gravel which contains a higher proportion of claylike fines.

Graniterock. The high quality level Graniterock aggregate was produced using a blend of the 1/2 inch, 1/4 inch, and crusher sand Graniterock products. Fifteen percent of the 1/2 inch product, 30 percent of the 1/4 inch product, and 55 percent crusher sand was used in the blend. The sand equivalent value of the high quality Graniterock aggregate is 60 and it contains 9.0 percent finer than the No. 200 mesh sieve. The low quality Graniterock aggregate was produced by adding 3.6 percent by weight of the Revlon kaolinite clay to the high quality aggregate. Resulting sand equivalent value for the low quality aggregate is 26 and the minus No. 200 mesh content is 12.0 percent. The high quality Graniterock aggregate is representative of high quality aggregate used in asphalt concrete. The low quality level material is representative of a quality construction aggregate which contains some claylike fines.

3.3 Aggregate Properties

Measured properties of each of the three aggregates at both high and low quality levels are tabulated in Table 6. Each property is discussed in following sections.

Gradation. Gradations of the aggregates were determined in accordance with Caltrans Method of Test 202. Gradations of each aggregate are plotted in Figures 2, 3, and 4 along with, for reference purposes only, Caltrans specifications for 1/2 and 3/4 inch coarse asphalt concrete mixtures (25). The gradations of San Bernardino and Fresno aggregates at both quality levels were finer on nearly all sieve sizes than permitted by the Caltrans 3/4 inch maximum course specification. The high quality Graniterock aggregate comes close to meeting specification requirements for 1/2 inch coarse asphalt concrete but is slightly finer than the specification limits on the 3/8 inch, No. 4, No. 8, and No. 200 sieves. Gradation of the low quality Graniterock aggregate is slightly finer than limits permit on the 3/8 inch, No. 4, No. 8, No. 100, and No. 200 sieves.

It is apparent that the aggregate gradations selected for the study do not meet Caltrans specifications for Type C asphalt concrete aggregate. However, the aggregate gradations do meet the criterion stipulated by the Request of Proposals (1). The use of Caltrans specification gradations was not the intent of this study. Moreover, the aggregate gradations selected are representative of local aggregates which are being used for "local" paving projects.

Sand Equivalent Value. Sand equivalent values of the aggregates were determined in accordance with Caltrans Method of Test 217. Values ranged from a low of 15 for low quality Fresno aggregate to a high of 60 for high quality Graniterock aggregate. According to Caltrans specifications for asphalt concrete, a minimum sand equivalent of 35 Type C is required (25). Only the high quality Graniterock material meets this requirement.

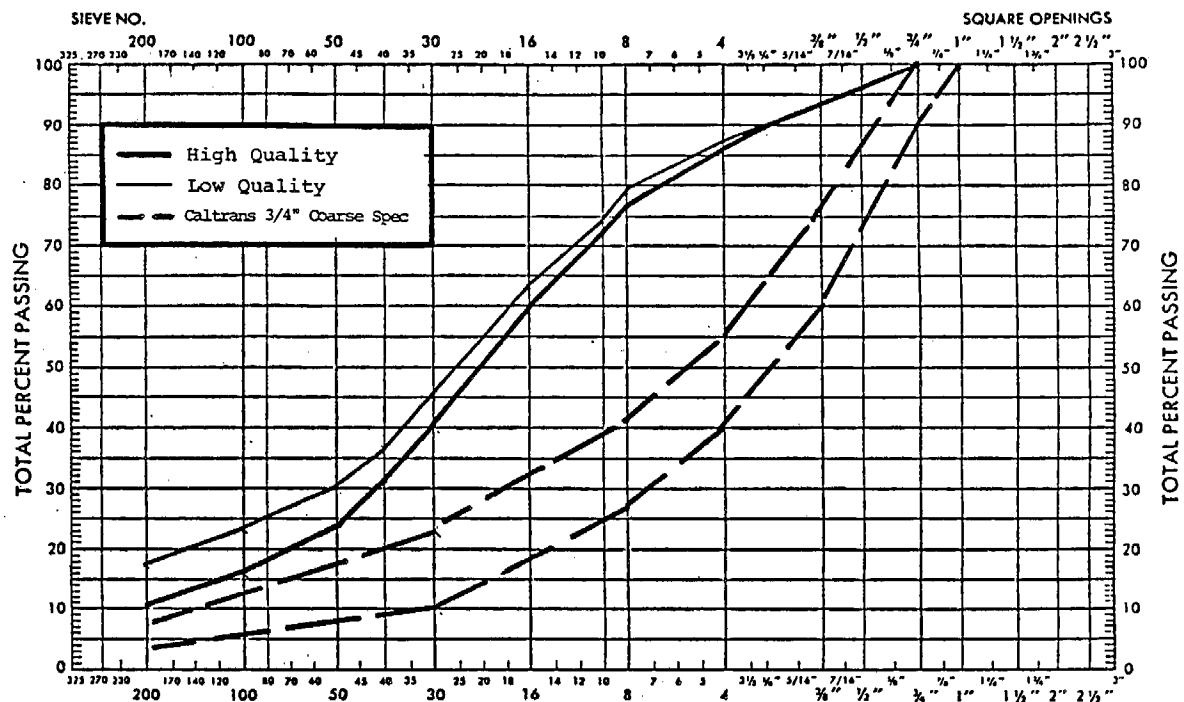
Centrifuge Kerosene Equivalent (C.K.E.). The C.K.E. values of the aggregates were determined in accordance with Caltrans Method of Test 303. K_c and K_f values for all aggregates meet Caltrans requirements of a 1.7 maximum for Type A and B asphalt concrete. Calculated approximate bitumen ratios (ABR) ranged from a low of 4.6 percent for the San Bernardino high quality aggregate to a high of 8.5 percent for the San Bernardino low quality material. Calculated surface areas (based on gradation) varied from a low of 48.4 ft²/lb for high quality Graniterock aggregate to a high of 75.9 ft²/lb for low quality San Bernardino aggregate.

Table 6. GRADATIONS, SAND EQUIVALENT, C.K.E. VALUES,
SURFACE AREA, ZETA POTENTIAL, AND ATTERBERG LIMITS
FOR HIGH AND LOW QUALITY AGGREGATES

Sieve Size	% Passing					
	San Bernardino		Fresno		Graniterock	
	High	Low	High	Low	High	Low
1" (25.0 mm)	100	100	100	100	100	100
3/4" (19.0 mm)	100	100	92	92	100	100
1/2" (12.5 mm)	96	96	82	82	100	100
3/8" (9.5 mm)	93	93	75	75	94	94
1/4" (6.3 mm)	89	90	67	67	83	84
#4 (4.75 mm)	86	87	62	62	69	70
#8 (2.36 mm)	77	79	54	51	51	53
#10 (2.00 mm)	72	74	53	49	47	49
#16 (1.18 mm)	60	63	48	46	37	39
#30 (600 um)	40	45	40	41	26	29
#40 (425 um)	32	37	36	37	22	25
#50 (300 um)	24	30	29	32	15	21
#100 (150 um)	16	23	16	20	13	16
#200 (75 um)	10.3	17.4	7.9	13.4	9.0	12.0
Sand Equivalent	29	18	29	15	60	26
C.K.E.						
¹ ABR	4.6	8.5	5.3	6.7	4.7	6.9
K _c	1.1	1.2	1.0	1.1	1.2	1.2
K _f	0.9	1.5	1.0	1.2	1.1	1.6
² S.A.	57.1	75.9	57.9	66.5	48.4	57.2
³ SA (Nitrogen Absorption) x 10 ³	39.8	57.4	89.4	111.6	13.8	30.7
⁴ Zeta Potential (mv)	-30.6	-30.8	-30.1	-33.7	-30.8	-31.7
Atterberg Limits						
Liquid Limit	22	21	22	22	22	17
Plastic Limit	N.P.	17	N.P.	21	N.P.	15
Plasticity Index	N.P.	4	N.P.	1	N.P.	2

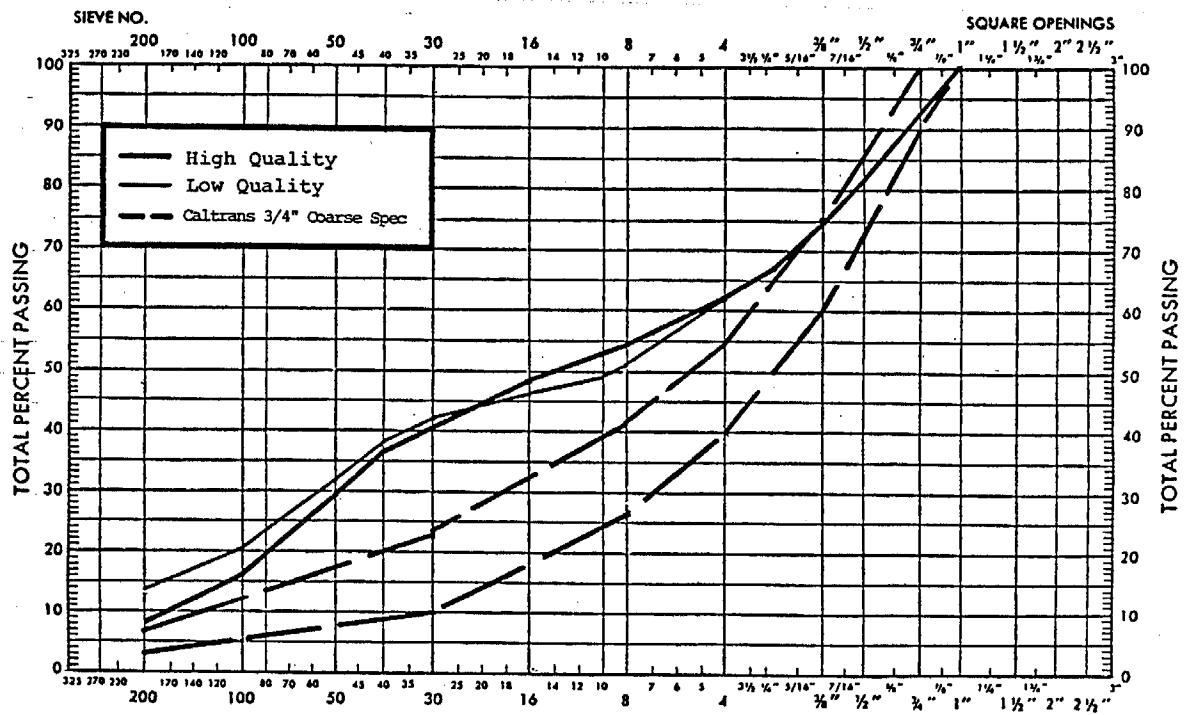
Notes:

- 1 Approximate Bitumen Ratio
- 2 Surface Area (ft²/lb) calculated base on gradation
- 3 Determined by BET Nitrogen absorption by Armak Company, McCook, Illinois. Results are in ft²/lb.
- 4 Determined by Armak Company using a Zeta Meter manufactured by Zeta Meter, Inc., New York.



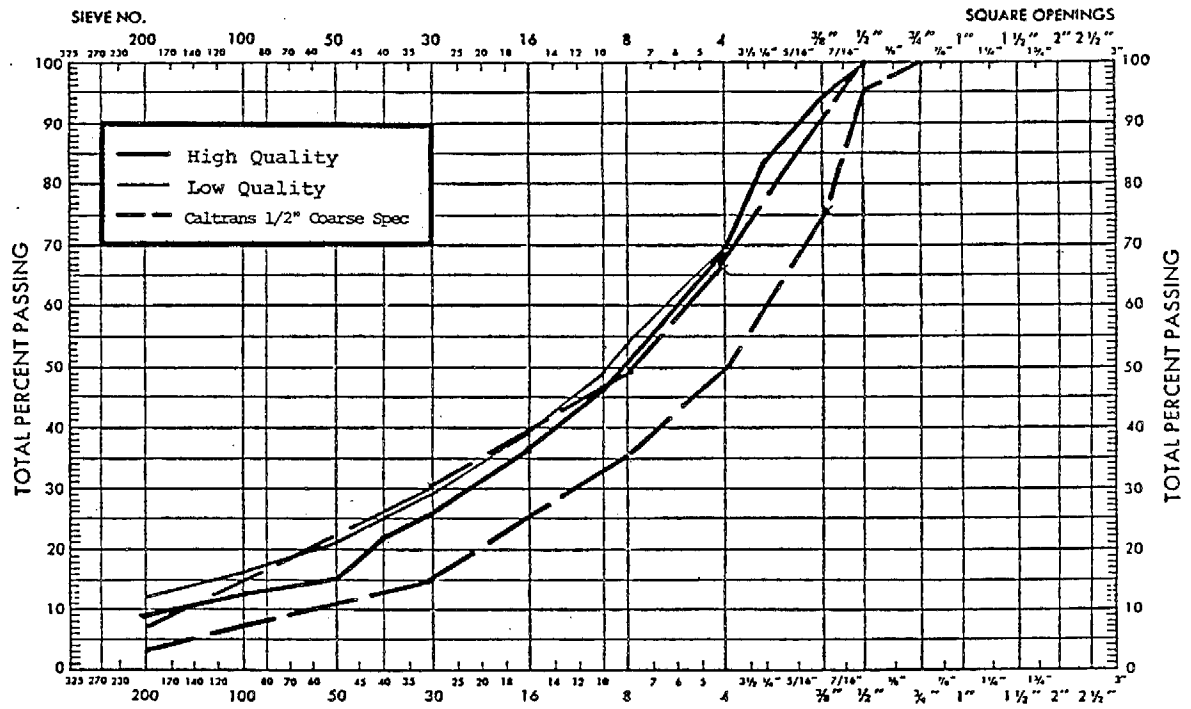
U.S. STANDARD SIEVES—ASTM DESIGNATION E 11

Figure 2. Gradations of San Bernardino High and Low Quality Aggregate and Caltrans 3/4 inch Maximum Coarse Gradation Specification



U.S. STANDARD SIEVES—ASTM DESIGNATION E 11

Figure 3. Gradations of Fresno High Quality and Low Quality Aggregate and Caltrans 3/4 inch Maximum Coarse Gradation Specification



U.S. STANDARD SIEVES—ASTM DESIGNATION E 11

Figure 4. Gradation of Graniterock High and Low Quality Aggregate and Caltrans 1/2 inch Maximum Coarse Gradation Specification

Surface Area By Nitrogen Absorption. Aggregate surface areas by nitrogen absorption (13) were determined by the Asphalt Research Laboratory of the Highway Chemicals Division of Armac Company of McCook, Illinois using a nitrogen absorption surface area analyzer. Aggregate surface areas determined in this manner ranged from a low of 13.8×10^3 ft²/lb for high quality Graniterock aggregate to a high of 111.6×10^3 ft²/lb for Fresno low quality level aggregate. High surface area indications for both low and high quality level Fresno aggregate are believed due to presence of a calcareous cementitious substance which is binding together fine aggregate portions together into agglomerations. When tested, the cementing agent releases CO₂ and tends to indicate an increased aggregate surface area. At least one-half of the reported surface area for Fresno aggregates is believed due to this release of CO₂ by the cementing agent.

Zeta Potential. Zeta potential (13) of the aggregates was determined by the Asphalt Research Laboratory of the Armac Company Highway Chemicals Division of McCook, Illinois using a Zeta Meter. Aggregate Zeta potential indicates the magnitude of the aggregate surface charge. Zeta potentials were found to be very similar for all aggregates tested and ranged from minus 30.1 millivolts to minus 33.7 millivolts.

Atterberg Limits. Atterberg limits of the aggregates were determined in accordance with Caltrans Method of Test 204. Results indicate the degree of plasticity of the minus No. 40 mesh fraction of the aggregate. Each high quality aggregate had non-plastic fines. Low quality Fresno aggregate had a plasticity index of 1, while that of low quality Graniterock aggregate was 2, and 4 for low quality San Bernardino aggregate. Results indicate that the low quality San Bernardino aggregate had fines with the highest degree of plasticity. Fines of the low quality Graniterock and low quality Fresno aggregate had a slight degree of plasticity.

Specific Gravity and Absorption. Coarse and fine aggregate specific gravities and absorptions were determined in accordance with Caltrans Methods of Test 206 and 207. Results are tabulated in Tables 7 and 8 for coarse (plus No. 4 mesh) and fine (minus No. 4 mesh) fractions.

Table 7

FINE AGGREGATE SPECIFIC GRAVITIES AND ABSORPTION

	<u>San Bernardino</u>	<u>Fresno</u>		<u>Graniterock</u>
		<u>High</u>	<u>Low</u>	
Bulk Specific Gravity	2.565	2.527	2.496	2.910
Apparent Specific Gravity	2.663	2.722	2.690	2.961
Bulk (SSD) Specific Gravity	2.602	2.599	2.568	2.927
Absorption; %	1.44	2.84	2.88	0.5%

Table 8

COARSE AGGREGATE SPECIFIC GRAVITIES AND ABSORPTIONS

	<u>San Bernardino</u>	<u>Fresno</u>	<u>Graniterock</u>
Bulk Specific Gravity	2.600	2.461	2.835
Bulk SSD Specific Gravity	2.617	2.535	2.866
Apparent Specific Gravity	2.644	2.658	2.925
Absorption; %	0.64	3.00	1.08

3.4 Asphalt Emulsions

Three asphalt emulsions were formulated and tested during this investigation. These emulsions were formulated for the aggregates considered in the study by the Highway Chemical Division of the Armak Company of McCook, Illinois. The emulsions which were formulated were a cationic slow set solvent free emulsion (CSS-0), a cationic medium set solvent free emulsion (CMS-0), and a conventional cationic medium set emulsion which contained 7 percent solvent (CMS-7). The purpose of considering the CMS-7 emulsion was to compare solvent free emulsified asphalts to traditional emulsions which contain solvent.

Base Asphalt. The base asphalt which was used in all asphalt emulsion formulations was an AR4000 asphalt cement produced by the Edgington Oil Company of Long Beach, California and supplied by Sahuaro Petroleum and Asphalt Company of Phoenix, Arizona. Crude from the Los Angeles Basin was used in the manufacture of this asphalt. Physical properties of the Edgington AR4000 and Caltrans specification requirements (25) are tabulated in Table 9. The asphalt meets all requirements of the specification for an AR4000 asphalt.

Emulsions. The three asphalt emulsions were produced at the Armak Asphalt Research Laboratory using a Model G-5 Charlotte Colloid Mill manufactured by Chemicolloid Laboratories, Inc. Selection of the specific emulsion formulations for the aggregates studied was based on aggregate gradation, zeta potential, and surface area. Asphalt emulsion formulations for the various aggregates were identical. Formulations of the soap solutions for the CSS-0, CMS-0, and CMS-7 emulsions are tabulated in Table 10.

Descriptions of the emulsifiers used in asphalt emulsion manufacture are contained in Table 11. The naptha (7% by total weight of emulsion) used as solvent with the CMS-7 emulsion was pure distilled reagent grade naptha produced by Varnish Makers and Painters (VM&P).

Table 9

PHYSICAL PROPERTIES OF UNAGED AND AGED
EDGINGTON AR4000 AND CALTRANS AR4000
SPECIFICATION REQUIREMENTS

<u>Test</u>	<u>AR4000</u>		<u>Caltrans Specification</u>
	<u>Unaged</u>	<u>Aged¹</u>	
Penetration, 77F, 100g, 5 sec; 1/10 mm	56	38	25 min. ²
Penetration, 39.2F, 200g, 60 sec 1/10 mm	17	13	-
Absolute Viscosity, 140F, 30 cm Hg; Poise	1919	3987	3000 - 5000 ²
Kinematic Viscosity, 275F; cSt	297	404	275 min ²
Softening Point; F	125.0	-	-
Ductility, 77F, 5 cm/min; cm	120+	120+	75 min. ²
Flash Point, COC; F	610	-	440 min. ³
Flame Point, COC: F	670	-	-
Solubility in Trichlorethylene, %	99.71	-	99 min. ³
<hr/>			
Rolling Thin Film Oven Loss; %	0.141	-	-
% Original Penetration	-	68	45 min.

Notes:¹Aged in accordance with Caltrans Method of Test 346²Specification value for aged residue.³Specification value for unaged material.

Table 10

EMULSIFIERS USED IN EMULSION
SOAP SOLUTION FORMULATIONS

<u>Emulsions</u>	<u>Emulsifiers*</u>
CSS-0	1.2% Redicote E-4868 0.25% Hydrochloric Acid 0.05% Redicote RD4442
CMS-0	0.8% Redicote E-5127 0.01% Hydrochloric Acid
CMS-7	0.3% Redicote E-4819 0.2% Redicote E-5127 0.15% Hydrochloric Acid

*Note: Percentages are by total weight of emulsion.

Table 11

DESCRIPTIONS OF EMULSIFIERS

<u>Constituent</u>	<u>Description</u>
*Redicote E4868	Liquid cationic slow set emulsifier for solvent free applications.
Redicote RD4442	Powdered protective colloid used to increase emulsion viscosity.
Redicote E5127	Liquid cationic slow setting emulsifier for solvent free applications.
Redicote E4819	Liquid cationic rapid setting emulsifier which can be used with emulsions containing solvent.

*Note: Redicote emulsifiers are produced by ArmaK Highway Chemicals Division, McCook, Illinois.

Physical characteristics of the CSS-0 emulsion in accordance with ASTM D244 (2) and Caltrans specification limits (25) for CSS-1h emulsions are tabulated in Table 12. The CSS solvent free emulsion meets all Caltrans requirements for a CSS-1h emulsion except for viscosity at 77F (17.7 seconds compared to the specification minimum of 20 seconds).

Physical characteristics of the CMS-0 and CMS-7 emulsions in accordance with ASTM D244 (2) and Caltrans specification limits (25) for CMS emulsions are tabulated in Table 13. The CMS-0 emulsion meets Caltrans requirements for a CMS-2h emulsion and the CMS-7 percent solvent emulsion meets requirements for a CMS-2 emulsion.

3.5 Sulfur-Extended-Asphalt Emulsions

Two different sulfur-extended-asphalt (SEA) emulsions were produced and studied in this investigation. Formulation and production of the experimental SEA emulsions were studied under a separate research contract with the Federal Highway Administration (24). The emulsions considered for purposes of this study were anionic slow set emulsions containing base stocks with a sulfur content below the asphalt saturation level of 20 percent by weight and a sulfur content above the saturation level. Sulfur extensions studied were 15 and 30 percent by weight of the total SEA binder. Cationic emulsions using SEA could not be studied as formulations available were not as stable as anionics (24).

Compatibility of the two SEA emulsion formulations with the project aggregates was determined by performing a preliminary mixing experiment with each emulsion and aggregate. Limited supplies of the SS-15 percent SEA and SS-30 percent SEA emulsions were on hand from the previous FHWA research project (24) and were used for experimentation.

Prewetting moisture contents used were those used with the solvent free emulsions (approximately one percent) and asphalt residue contents used were between 5 and 7 percent. Combinations of the six project aggregates and the SS-15 and SS-30 percent SEA emulsions tested were found to mix and coat very well. Thus, emulsions of the same formulation as those studied in this preliminary mixing experiment were produced by Petroleum Sciences, Inc. of Spokane, Washington for use in this project.

Table 12

TEST RESULTS FOR THE CSS-0 EMULSION AND CALTRANS
SPECIFICATION REQUIREMENTS FOR CSS-1h EMULSIONS

Tests on Emulsion	CSS-0	Caltrans Specification
Viscosity, Saybolt Furol, 77F; sec.	17.7	20 - 100
Storage Stability, 24 hr; %	-0.5	1.0 max.
5 Day Settlement; %	2.4	5.0 max.
Particle Charge Test	Positive	Positive
Sieve Test; %	0.09	0.10 max.
Cement Mixing Test; %	1.9	2.0 max.
Distillation		
Oil Distillate; %	0.0	-
Residue; %	59.5	57.0 min.
Coating Ability And		
Water Resistance	SB ¹ F GR	-
Coating, Dry Aggregate	G ² G G	-
Coating, After Spraying	P F P	-
Coating, Wet Aggregate	P G G	-
Coating, After Spraying	P P P	-
<u>Tests on Residue From Distillation</u>		
Penetration, 77F, 100g, 5 sec; 1/10 mm	60	40 - 90
Penetration, 39.2F, 200g, 60 sec; 1/10 mm	18	-
Absolute Viscosity, 140F, 30 cm Hg; Poise	1694	-
Kinematic Viscosity, 275F; cSt	304	-
Softening Point; F	122.5	-
Ductility, 77F, 5 cm/min; cm	120+	40 min.
Solubility in Trichlorethylene; %	99.77	97.5 min.
Specific Gravity	1.01	-

Notes:

¹SB = San Bernardino, F = Fresno, GR = Graniterock
²G = Good, F = Fair, P = Poor

Table 13

TEST RESULTS FOR CMS-0 AND CMS-7
EMULSIONS AND CALTRANS SPECIFICATION
REQUIREMENTS FOR CMS-2 AND CMS-2h EMULSIONS

<u>Tests on Emulsion</u>	<u>CMS-0</u>	<u>CMS-7</u>	<u>Caltrans Specification</u>	
Viscosity, Saybolt Furol, 77F; sec.	22.8	90.9	20 - 100	
Storage Stability, 24 hr; %	+0.7	-0.4	1.0 max.	
5 Day Settlement; %	1.7	-1.4	5.0 max.	
Particle Charge Test	Positive	Positive	Positive	
Sieve Test; %	0.04	0.38	0.10 max.	
Distillation				
Oil Distillate; %	0.0	6.5	12 max.	
Residue; %	65.5	66.8	65 min.	
Coating Ability And				
Water Resistance	<u>SB</u> ¹	<u>F</u>	<u>GR</u>	-
Coating, Dry Aggregate	G ²	G	G	-
Coating, After Spraying	G	G	P	-
Coating, Wet Aggregate	G	G	G	-
Coating, After Spraying	P	F	P	-
<u>Tests on Residue From Distillation</u>				
Penetration, 77F, 100g, 5 sec; 1/10 mm	60	143	40 - 90 ³ 100-250 ⁴	
Penetration, 39.2F, 200g, 60 sec; 1/10 mm	18	50	-	
Absolute Viscosity, 140F, 30 cm Hg; Poise	1694	742	-	
Kinematic Viscosity, 275F; cSt	304	203	-	
Softening Point; F	122.5	106.5	-	
Ductility, 77F, 5 cm/min; cm	120+	120+	40 min.	
Solubility in Trichlorethylene; %	99.61	99.76	97.5 min.	
Specific Gravity	1.01	.099	-	

Notes:¹SB = San Bernardino, F = Fresno, GR = Graniterock²G = Good, F = Fair, P = Poor³For CMS-2h⁴For CMS-2

Base Sulfur-Extended-Asphalts. The base asphalt used in producing the SEA emulsion base stocks was a blend of hard and soft asphalt emulsion bases produced by Edgington Oil Company of Long Beach, California. Edgington AR4000 (which was used as the base for the asphalt emulsions used in this study) was not available as the base asphalt for the sulfur-extended-asphalt emulsions. In order to provide a base asphalt similar to that used in asphalt emulsion formulations in this study, two Edgington emulsion base stocks (hard and soft) produced from the same crude source were blended to give an initial absolute viscosity at 140F of 1900 poise which is equivalent to that of the Edgington AR4000 used in the asphalt emulsions. Proportions used in the blend were 90 percent hard base and 10 percent soft base.

For laboratory characterization purposes, the SEA's were made by adding the appropriate amount of laboratory grade crystalline sulfur obtained from Van Waters and Rogers to the blended Edgington emulsion base at 275F and stirring by hand at 275F until homogeneous. Physical properties of the blended base stock and SEA's at 15 and 30 percent extensions are tabulated in Table 14.

Sulfur-Extended-Asphalt Emulsions. The anionic SS-15 and SS-30 SEA emulsions were produced by Petroleum Sciences, Inc. in a laboratory Charlotte Colloid Mill manufactured by Chemicolloid Laboratories, Inc. Emulsifiers used in formulation of these emulsions are shown in Table 15 and descriptions of these emulsifiers are shown in Table 16. Details of experiments performed during formulation studies with SEA base stocks are contained in FHWA report, "Highway Binder Materials From Modified Sulfur-Water Emulsions" (24). No solvent was used in production of the SEA emulsions.

Physical properties of the SEA emulsions and emulsion residues in accordance with ASTM D244 (2) and Caltrans specification limits (25) for anionic SS-1h emulsions are tabulated in Table 17. A modified distillation procedure was used to obtain the SEA residues as the ASTM D244 requirement of heating the emulsions above 300F may excessively age and harden

Table 14

PHYSICAL PROPERTIES OF BLENDED EDGINGTON EMULSION
BASE STOCK AND 15 AND 30 PERCENT
SULFUR-EXTENDED-ASPHALTS

Test	Base Asphalt		15% SEA		30% SEA	
	Orig.	Aged ¹	Orig.	Aged ¹	Orig.	Aged ¹
Penetration, 77F 100g, 5 sec; 1/10 mm	74	38	115	71	119	54
Penetration, 39.2F, 200g, 60 sec; 1/10 mm	19	15	28	19	25	16
Absolute Viscosity, 140F, 30cm Hg; Poise	1902	3407	891	1708	1220	3630
Kinematic Viscosity, 275F; cSt	267	349	140	205	149	236
Softening Point; F	122	-	110	123	114	128
Ductility, 77F, 5 cm/min; cm	120+	120+	120+	120+	120+	47
Flash Point, COC; F	535	-	-	-	-	-
Flame Point, COC; F	625	-	-	-	-	-
Solubility in Trichlorethylene, %	99.80	-	-	-	-	-
<hr/>						
Rolling Thin Film Oven Loss; %	0.20		3.26		4.64	
% Original Penetration at 77F	51		62		45	
² Aging Index, 60C Viscosity	1.79		1.92		2.97	

Notes:

- ¹ Aged in accordance with Caltrans 346
- ² Calculated as aged absolute viscosity divided by original absolute viscosity.

Table 15

EMULSIFIERS USED IN SULFUR-EXTENDED-ASPHALT EMULSIONS

<u>Emulsion</u>	<u>Constitutents</u> ¹
SS 15% SEA	0.78% Pamak WCFA ² 2.40% Vinsol NVX 0.60% Marasperse CE 0.15% Sodium Hydroxide 0.07% Natrosol 250 HR
SS 30% SEA	0.96% Pamak WCFA ² 3.00% Vinsol NVX 0.80% Marasperse CE 0.19% Sodium Hydroxide 0.08% Natrasol 250 HR

Notes:

- 1 Percentages based on total weight of emulsion
- 2 Reacted with sulfur at 275F (135C) for 2 hours prior to emulsion production.

Table 16

DESCRIPTIONS OF EMULSIFIERS USED IN
SULFUR-EXTENDED-ASPHALT EMULSIONS (24)

<u>Emulsifier</u>	<u>Description</u>
PAMAK WCFA ¹	Anionic rapid set tall oil emulsifier
VINSOL NVX ¹	Anionic slow set emulsifier, abdietic acid
MARASPERSE CE ²	Dispersant for slow set emulsions, sodium ligno-sulfonate
NATRASOL 250 HR ¹	Hydroxyethyl cellulose viscosity builder

Notes:

- ¹Manufactured by Hercules, San Francisco, California
- ²Manufactured by American Can Company, Houston, Texas

Table 17.

TEST RESULTS FOR SULFUR-EXTENDED-ASPHALT EMULSIONS
AND CALTRANS SPECIFICATION FOR SS-1h EMULSION

<u>Tests on Emulsion</u>	<u>SS 15% SEA</u>	<u>SS 30% SEA</u>	<u>SS-1h Specification</u>
Viscosity, Saybolt Furol, 77F; sec	10.2	50.1	20-100
Storage Stability, 24 hr; %	4.6	21.2	1 max.
5 Day Settlement; %	8.3	33.0	5 max.
Sieve Test; %	.01	.03	0.1 max.
Cement Mixing Test; %	4.3	12.1	2.0 max.
Distillation			
Oil Distillate; %	0.0	0.0	-
Residue; %	63.0	59.5	57 min.
<u>Coating Ability and Water Resistance</u>	<u>SB</u> <u>F</u> <u>GR</u>	<u>SB</u> <u>F</u> <u>GR</u>	
Coating, Dry Aggregate	G G G	G G G	-
Coating, After Spraying	P P P	P P P	-
Coating, Wet Aggregate	G G G	G G G	-
Coating, After Spraying	P P P	P P P	-
<u>Tests on Residue From Distillation</u>			
Penetration, 77F, 100g, 5 sec; 1/10 mm	69	51	40-90
Penetration, 39.2F, 200g, 60 sec; 1/10 mm	22	14	-
Absolute Viscosity, 140F, 30 cm Hg; Poise	1287	1799	-
Kinematic Viscosity, 275F; cSt	233	278	-
Softening Point; F	124	130	-
Ductility, 77F, 5 m/min; cm	120+	120+	40 min.
Specific Gravity	1.059	1.157	-

the residue (24). The procedure used consisted of heating the emulsions to 275F in a boiling flask while sweeping with carbon dioxide. Details of this procedure are contained in reference 24. The SEA emulsions do not meet Caltrans specifications for SS-1h emulsion for storage stability, 5 day settlement, and cement mixing and the SS-15 does not meet the viscosity requirements. Solubilities were not determined as sulfur is not soluble in trichloroethylene. These results are similar to those obtained with the experimental emulsions (24).

4.0 EXPERIMENTAL DESIGN AND DATA ANALYSIS

4.1 Asphalt Emulsions

The experiment is designed as a completely randomized 3 by 2 by 3 cell fixed factorial model with two replications per cell. The experiment compares data for the CSS-0 and CMS-0 emulsions to those for mixtures containing the CMS-7 emulsion. The experimental factorial is shown in Figure 5. The model for analysis is:

$$Y_{ijkl} = \mu + A_i + Q_j + E_k + AQ_{ij} + AE_{ik} + QE_{jk} + AQE_{ijk} + \epsilon_{(ijk)l}$$

in which:

Y_{ijkl}	=	Response variable (density, stabilometer, etc.)
μ	=	Effect of the overall mean
A_i	=	Effect of aggregate type
Q_j	=	Effect of aggregate quality level
E_k	=	Effect of emulsion type
AQ_{ij}	=	Effect of aggregate-quality level interaction
AE_{ik}	=	Effect of aggregate-emulsion interaction
QE_{jk}	=	Effect of quality level-emulsion interaction
AQE_{ijk}	=	Effect of aggregate-quality level-emulsion interaction
ϵ_{ijkl}	=	Experimental error

The data were subjected to conventional three-way analysis of variance (ANOVA) techniques (26) and tested significance at the 95 and 99 percent confidence levels by the F-test (26). Prior to analysis, homogeneity of variance was checked using the Foster and Burr q-test (27). When necessary, appropriate data transformations were made to comply with variance homogeneity constraints. Following ANOVA, data were ranked by the Newman-Keuls means ranking procedure (28) at the 95 percent confidence level to identify significant differences in the data and to aid in interpretation.

		EMULSION		QUALITY LEVEL		AGGREGATE	
		SAN BERNARDINO		FRESNO		GRANITEROCK	
		HIGH	LOW	HIGH	LOW	HIGH	LOW
C	S	—	—	—	—	—	—
		—	—	—	—	—	—
S	O	—	—	—	—	—	—
		—	—	—	—	—	—
C	M	—	—	—	—	—	—
		—	—	—	—	—	—
S	O	—	—	—	—	—	—
		—	—	—	—	—	—
C	M	—	—	—	—	—	—
		—	—	—	—	—	—
S	7	—	—	—	—	—	—
		—	—	—	—	—	—

Figure 5. Experimental Matrix, Asphalt Emulsions


Degrees of freedom for the ANOVA are:

<u>Source</u>	<u>Degrees of Freedom</u>
A_i	2
Q_j	1
E_k	2
AQ_{ij}	2
AE_{ik}	4
QE_{jk}	2
AQE_{ijk}	4
Error	18
Total	35

Two complete mixture designs were performed at random for each emulsion-aggregate combination contained in the experimental matrix. Physical properties of mixtures at the design binder content from each mix design were analyzed. With several of the test procedures, three replications per cell were used instead of two in order to increase the power of the analysis. In these cases, error degrees of freedom are 36 and total degrees of freedom are 53. Required modifications in the analyses (critical F-values, Newman-Keuls ranking, etc.) were made.

4.2 Sulfur-Extended-Asphalt Emulsions

The sulfur-extended-asphalt emulsion experiment was designed essentially in the same manner as the asphalt emulsion experiment, except that for this experiment, data for the SS 15 and SS 30 percent SEA emulsions are compared to those for the CMS 7 emulsion. The experimental factorial for this experiment is shown in Figure 6. The experiment is sequentially randomized and uses data developed during the asphalt emulsion portion of the study for the CMS-7 emulsion and data developed using the SEA emulsions. The analytical model, analysis techniques, and degrees of freedom are the same as used for the asphalt emulsion experiment.



	SAN BERNARDINO		FRESNO		GRANITEROCK	
	HIGH	LOW	HIGH	LOW	HIGH	LOW
S	—	—	—	—	—	—
S	—	—	—	—	—	—
15	—	—	—	—	—	—
S	—	—	—	—	—	—
S	—	—	—	—	—	—
30	—	—	—	—	—	—
C	—	—	—	—	—	—
M	—	—	—	—	—	—
S	—	—	—	—	—	—
7	—	—	—	—	—	—

Figure 6. Experimental Matrix,
Sulfur-Extended-Asphalt Emulsions

5.0 MIXTURE DESIGNS AND SPECIMEN TESTING

5.1 Introduction to Procedure

Currently, no standardized procedure for the mixture design of emulsified asphalt paving mixtures exists even though much work and considerable research has been performed on the subject (32). Presently, mixture design methods have been developed by The Asphalt Institute (3), U.S. Forest Service (33), Chevron (9), Federal Highway Administration (34) K. E. McConnaughay, Inc. (32), University of Illinois (35), Purdue (36), ArmaK (37), University of Arizona (38), and University of Mississippi (39). Detailed reviews of procedures and requirements of these methods are available (32, 40).

Factors which need to be considered in the design of an emulsified-asphalt-paving mixture are (32):

1. Asphalt emulsion type
2. Aggregate type
3. Amount of prewetting water required to obtain adequate aggregate coating
4. Amount of emulsion
5. Amount of or fluids required in the mixture to achieve adequate compaction
6. Type of compaction procedure
7. Method of mixture curing
8. Strength of the compacted mixture
9. Water resistance of the mixtures
10. Criteria used to select appropriate mixture formula.

Most design procedures address many or all of the above factors in some manner. Methods used for selection of emulsion, aggregate type and amount of pre-wetting water required for aggregate coating are similar with most methods. However, selection of amount of emulsion, fluids for compaction, compaction method, curing procedure, testing procedures, and evaluation of results may differ widely. It has been noted that differences in compaction and curing methods influence results of test values (32).

The mixture design procedure used during this study generally follows that proposed by The Asphalt Institute in publication PCD-1 (3). Basically, the procedure consists of determining required moisture for proper coating, mechanically mixing emulsion and aggregate, loose curing the mixtures to obtain appropriate fluids content for optimum compaction, compacting the air cured mixture using light Hveem compaction followed by static double plunger leveling, and curing by dessicating to constant weight and modulus. Cured specimens were tested and analyzed according to methods designed for and used for determining properties of quality hot-mix asphalt concrete mixtures. Details of each portion of the mixture design procedure are discussed in following sections.

5.2 Selection of Binder Contents

The PCD-1 (3) method uses the oil ratio from the C.K.E. (Caltrans 303) procedure of the aggregate as the basis for selecting emulsion contents for preparing mix design specimens. Trial emulsion contents (corrected to a 60 percent residue content) of 1.1, 1.4, and 1.7 times the oil ratio are used to prepare the specimens. Oil ratios and trial emulsion residue contents (based on a 60 percent residue) determined in this manner are tabulated in Table 18. As seen in Table 18, trial emulsion residue contents varied from a low of 3.0 percent to a high of 8.7 percent. Several of the contents (SBH, FH, and GRH) were believed to be unrealistically low considering aggregate surface areas and binder contents which would be required for quality hot-mixed asphalt concrete. Trial binder contents selected for mixture design purposes were selected considering the recommended values in Table 18 and using experience with asphalt concrete mixtures to adjust the trial emulsion contents to more appropriate values. Trial emulsion contents used in mixture designs with the asphalt emulsion experiment are tabulated in Table 19 and for the SEA emulsion experiment in Table 20. For the SEA emulsion mixture designs, the weight of emulsion used was adjusted using ratios of residue specific gravities to provide residue volumes equivalent to those obtained using the asphalt emulsions.

Table 18

TRIAL EMULSION RESIDUE CONTENTS AS DETERMINED
BY 1.1, 1.4, AND 1.7 TIMES THE OIL RATIO
FROM THE C.K.E. PROCEDURE; %

<u>C.K.E. Multiplier</u>	<u>Aggregate</u>					
	<u>SBH*</u>	<u>SBL</u>	<u>FH</u>	<u>FL</u>	<u>GRH</u>	<u>GRL</u>
1.1	3.0	5.6	3.5	4.4	3.1	4.6
1.4	3.9	7.1	4.4	5.6	3.9	5.8
1.7	4.7	8.7	5.4	6.8	4.8	7.0

*Notes:

SB = San Bernardino, F = Fresno, GR = Graniterock
H = High Quality, L = Low Quality

Table 19

EMULSION RESIDUE CONTENTS USED IN
MIXTURE DESIGNS, ASPHALT EMULSION EXPERIMENT; %

<u>Residue Level</u>	<u>Aggregate</u>					
	<u>SBH</u>	<u>SBL</u>	<u>FH</u>	<u>FL</u>	<u>GRH</u>	<u>GRL</u>
Low	5.0	6.0	5.0	6.0	4.7	5.5
Medium	6.0	7.2	6.0	7.0	5.7	6.5
High	7.0	8.5	7.0	8.0	6.7	7.5

Table 20

EQUIVALENT ASPHALT EMULSION RESIDUE CONTENTS USED IN
MIXTURE DESIGNS, SULFUR-EXTENDED-ASPHALT MIXTURES; %

<u>Residue Level</u>	<u>Aggregate</u>					
	<u>SBH</u>	<u>SBL</u>	<u>FH</u>	<u>FL</u>	<u>GRH</u>	<u>GRL</u>
Low	6.0	6.5	6.0	6.5	4.5	5.0
Medium	7.0	7.5	7.0	7.5	5.5	6.0
High	8.0	8.5	8.0	8.5	6.5	7.0

5.3 Prewetting Water For Proper Coating

Amounts of water required for obtaining appropriate coating of aggregate with the emulsion were determined using the mixing test procedure as outlined in PCD-1 manual (3). Trial batches, 2200 grams in weight, were placed in the mixing bowl of a Hobart mixer, the specific amount of water being studied added uniformly to the aggregate and mixed for 1 minute at low speed using a wire whip. Then, the emulsion was added to the mixture and mixed for an additional minute. Emulsion amounts studied were approximately 1.4 times the aggregate C.K.E value as recommended by PCD-1 (3). However, in several cases, the amount of emulsion used was increased when the mixtures appeared to be low in binder. Moisture contents studied varied from 0 to 5 percent. Coarse particles in Fresno and San Bernardino aggregate were found to be difficult to coat with emulsion. However, it was found that if the prewet water was mixed with the aggregate and the aggregate placed in a sealed container for 2 to 4 days, that the coarse fractions coated better. This is believed to be due to more uniform dispersion of the moisture within the aggregate. Aggregate prewetting water requirements were selected as the minimum amount of water which would provide a maximum degree of aggregate coating by the emulsion. Aggregate prewetting requirements are tabulated in Table 21. With the anionic sulfur-extended-asphalt emulsions, it was found that aggregates coated adequately using lower prewetting water contents than used with the cationic asphalt emulsions.

5.4 Optimum Fluids For Compaction

The optimum mixture fluids contents for specimen compaction were determined following the PCD-1 (3) procedure. The procedure consists of mixing a 3300 gram batch of aggregate containing the appropriate amount of prewetting water with an emulsion content approximately equal to 1.4 times the aggregate oil ratio determined using the C.K.E. procedure. In several cases, emulsion contents used were greater than 1.4 times the C.K.E value. Following mixing at low speed for 1 minute in the Hobart mixer, the mixture was removed from the mixing bowl, placed on a sheet of release paper and split into three equivalent portions each weighing approximately 1100 grams. One portion is compacted immediately

Table 21

AGGREGATE PREWETTING MOISTURE REQUIREMENTS, %

<u>Emulsion</u>	<u>Aggregate</u>					
	<u>SBH</u>	<u>SBL</u>	<u>FH</u>	<u>FL</u>	<u>GRH</u>	<u>GRL</u>
CSS-0	0.9	1.4	1.5	1.5	0.8	0.8
CMS-0	1.2	1.4	2.0	2.0	0.9	1.1
CMS-7	1.2	0.7	2.0	2.0	0.9	1.1
SS-15	0.5	1.0	1.0	1.0	0.5	0.5
SS-30	0.5	1.0	1.0	1.0	0.5	0.5

Table 22

OPTIMUM FLUIDS REQUIREMENTS FOR COMPACTION, %

<u>Emulsion</u>	<u>Aggregate</u>					
	<u>SBH</u>	<u>SBL</u>	<u>FH</u>	<u>FL</u>	<u>GRH</u>	<u>GRL</u>
CSS-0	10.0	11.0	10.0	12.0	8.5	8.5
CMS-0	10.5	11.0	10.0	12.0	9.0	9.0
CMS-7	10.5	10.5	10.0	10.5	8.0	8.0
SS-15	10.0	10.5	12.0	12.0	7.5	8.0
SS-30	10.0	10.5	11.0	11.5	8.0	8.0

with a kneading compactor in a 4 inch diameter mold using approximately 25 blows at 250 psi. Following kneading compaction, the specimen is further compacted using a double plunger procedure and static loading to 40,000 pounds using a vertical loading rate of 0.05 in/min. Loading is stopped if water is extruded from the specimen during the static compaction operation. Immediately following compaction, the thickness of the specimen is measured, the specimen extracted, and its weight determined. The specimen is then dried to constant weight at 230F and the dry weight determined. Knowing the specimen thickness and diameter (4.00 inches), the volume of the specimen may be calculated. Specimen dry density may be calculated based on calculated volume and dry weight according to the following formula:

$$D = \frac{0.3028 \times W_d}{Th} \quad (1)$$

in which:

D = Dry specimen density (pcf)
W_d = Dry weight of specimen (grams)
Th = Specimen thickness (inches)

The water content of the specimen at compaction is determined based on the weight loss which occurred during oven drying. Total fluids at compaction is determined as the sum of the moisture content at compaction plus the emulsion residue content expressed as a percentage by weight of aggregate.

The second two mixture portions are air cured while monitoring their weights until weight losses of approximately 15 and 30 grams are obtained. Weight losses occur as moisture evaporates from the mixtures. A 15 gram weight loss indicates a loss of approximately 30 to 40 percent of water in the emulsion, while the 30 gram loss indicates approximately 60 to 80 percent loss of water in the emulsion (based on 1100 grams of aggregate and a 10 percent emulsion content with a residue content of approximately 60 percent). When the 15 and 30 gram weight losses are achieved, each specimen is compacted, measured, extracted, and oven dried as with the first specimen. Density and fluids content are determined.

Plots of dry density versus total fluids content were made and the optimum fluids content for compaction determined as the total fluids content which gave the highest density. Fluids contents used for compaction of mixture design specimens are shown in Table 22. Data and plots for these determinations for each emulsion-aggregate combination are contained in Appendix A. It is noted that for several of the emulsion aggregate combinations, the fluids content for compaction was not chosen as the value which gave the highest density as the mix was becoming too dry for the specimen to bind together properly.

5.5 Specimen Fabrication

For each aggregate emulsion combination, two complete mixture designs were performed. Each mixture design consisted of compacting three specimens at each of the three emulsion residue contents for the specific aggregate being investigated. Three specimens were mixed at the same time in the Hobart mixer using 3300 gram batches of aggregate which had the appropriate amount of prewet water for coating (Section 5.3) added 2 to 4 days prior to mixing. The appropriate amount of emulsion to give the desired residue content was added and the mixture was mixed for one minute at low speed. Following mixing, the mixture was placed on a sheet of release paper, weighed, and then allowed to air cure while monitoring its weight until the predetermined fluids content for compaction was attained. Attainment of the fluids content for compaction was determined by first calculating the total fluids content of the mixture at mixing considering both aggregate prewet moisture and the emulsion content expressed as a percentage of dry aggregate weight. The difference between the optimum fluids content for compaction percentages (Section 5.4) and total fluids at mixing was determined (on a percentage basis by weight of dry aggregate) and multiplied by the dry aggregate weight to yield the loss in moisture required to reach the desired fluids content for compaction. Specimens from the mixture were compacted when the calculated weight loss was attained. In several cases at low emulsion contents, it was necessary to add a small amount of water to the mix to have the appropriate fluids for compaction. Compaction consisted of placing the mixture in the 4 inch diameter

mold, rodding 25 times with a round-nose 3/8 inch diameter rod, and then compacting using 25 blows of the kneading compactor at 250 psi followed by static double plunger loading to 40,000 pounds.

5.6 Mixture Curing

Immediately following completion of compaction, the weight of the specimen and the mold was determined and recorded. Molds containing the specimens were placed in a horizontal position on their side and permitted to air cure at ambient temperature ($75 \pm 3^\circ\text{F}$) for 2 days. Following the 2 day air curing period, specimens in the molds were again weighed. In this manner the amount of moisture which evaporated from the specimen during the 2 day air curing period was determined by subtracting the 2 day weight from the weight obtained immediately following compaction. Specimens were then extracted from the mold and immediately weighed to determine the weight loss of the specimen which occurred during extraction. Specimens were temperature conditioned to $77 \pm 1^\circ\text{F}$ in a laboratory temperature control chamber and their resilient modulus (41) determined using a Mark IV Resilient modulus device manufactured by the Retsina Corporation of El Cerrito, California. A 0.05 second response period and loads of 10 pounds were used.

Following determination of resilient modulus, specimens were placed in large scale desiccating chambers constructed of 12 inch diameter PVC pipe. A schematic of the dessicators used is shown in Figure 7. Approximately 200 grams of flaked calcium chloride was placed in the bottom of each desiccator to aid in absorbing moisture. Desiccators were sealed by attaching 1/2 inch thick plexiglass plates to the top of the desiccators. A vacuum of 10 to 15 inches of mercury is pulled on the dessicators. This procedure is essentially the same as that used in the PCD-1 manual (3) except that a lesser vacuum than with PCD-1 was used. At high vacuums, the possibility of specimen damage exists due to formation of expansive pressure inside the specimen.

Specimens were continuously desiccated except when being tested. Weight and modulus of the specimens were monitored at 7, 14, and 21 days after compaction to determine when a constant weight and maximum

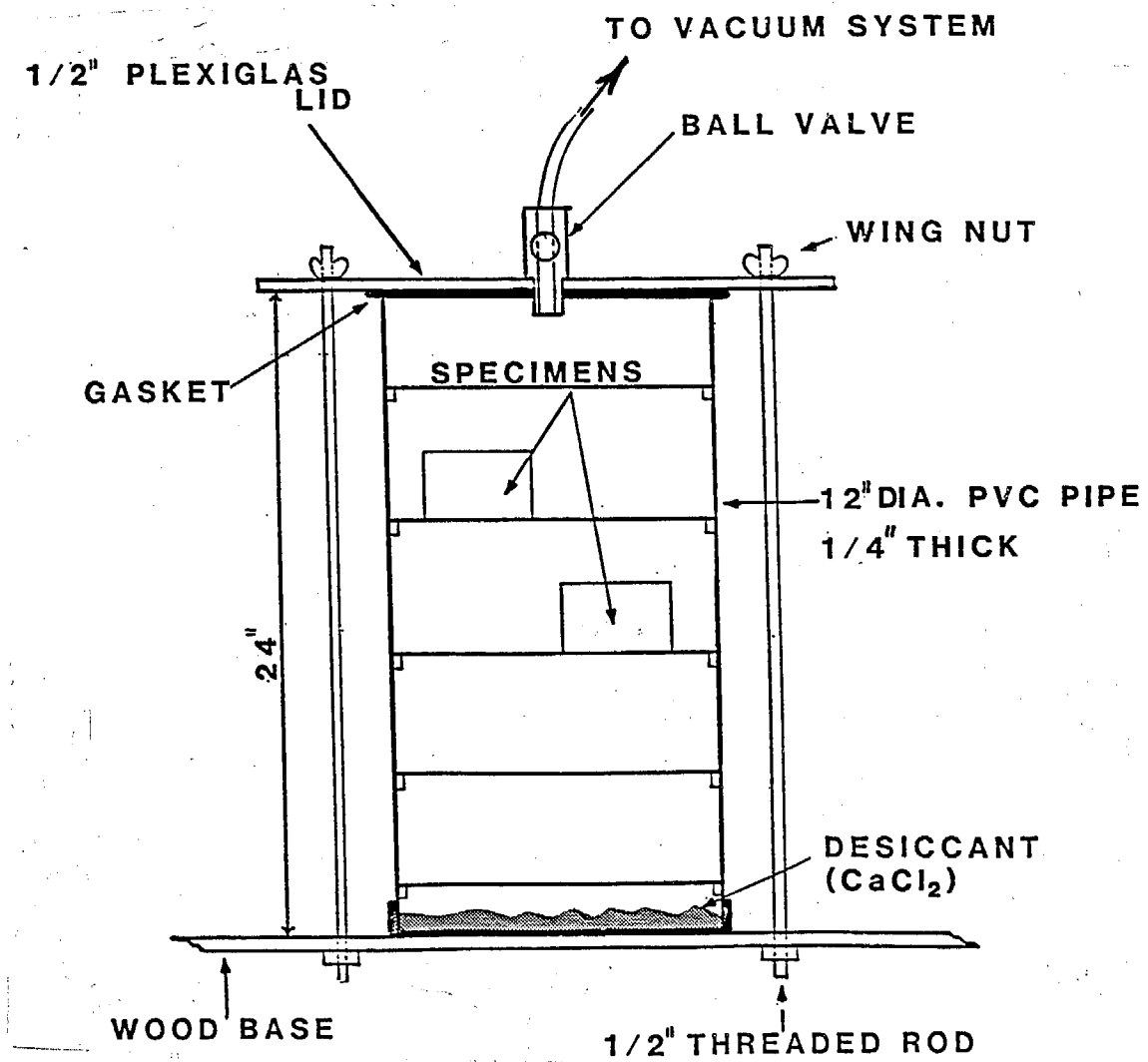


Figure 7. Schematic Diagram of Large Scale Vacuum Desiccation Chamber

modulus were reached. For modulus determinations at 7, 14, and 21 days of desiccation, a 15 pound load was used. The calcium chloride was replaced at each monitoring period. Attainment of constant weight and maximum modulus indicate that the specimens had reached a fully cured condition in which, for all practical purposes, all water was removed from the specimen. Typical plots of the weight loss and modulus gain during vacuum desiccation are shown in Figures 8 and 9 respectively. For testing purposes, achievement of a weight loss in the specimens of less than 3 grams during 7 days of desiccation was used as the criteria for determining when the fully cured condition had been reached. Most specimens reached the full cure condition at 21 to 28 days of desiccation. Several of the specimen sets reached the full cure condition at 14 days and several sets required from 35 to 42 days.

In general, specimens at higher emulsion contents reached the full cure condition earlier than specimens which contained lower emulsion contents. This is believed due to the greater degree of aerating (water evaporation) required to reach optimum fluids for compaction levels for specimens containing the higher emulsion contents. Additionally, many specimens containing the CMS-7 emulsion tended to require longer desiccation periods than specimens with the other emulsions.

5.7 Testing Procedures During The Mixture Design Phase

When specimens reached the full cure condition, their properties and characteristics were analyzed using conventional Hveem mix design techniques. Density-voids relationships, stabilometer values, and cohesiometer values were determined. In addition, film stripping tests were performed. In several cases, slight modifications to the test procedures were required due to the use of emulsified asphalt mixtures. Testing procedures used are discussed in following sections.

Film Stripping. Tests were performed with each aggregate source and emulsion considered in accordance with Caltrans Method of Test 302 (42). Since tests are performed only with the coarse (plus No. 4 mesh) material, testing could only be performed by aggregate source and not by high and low quality

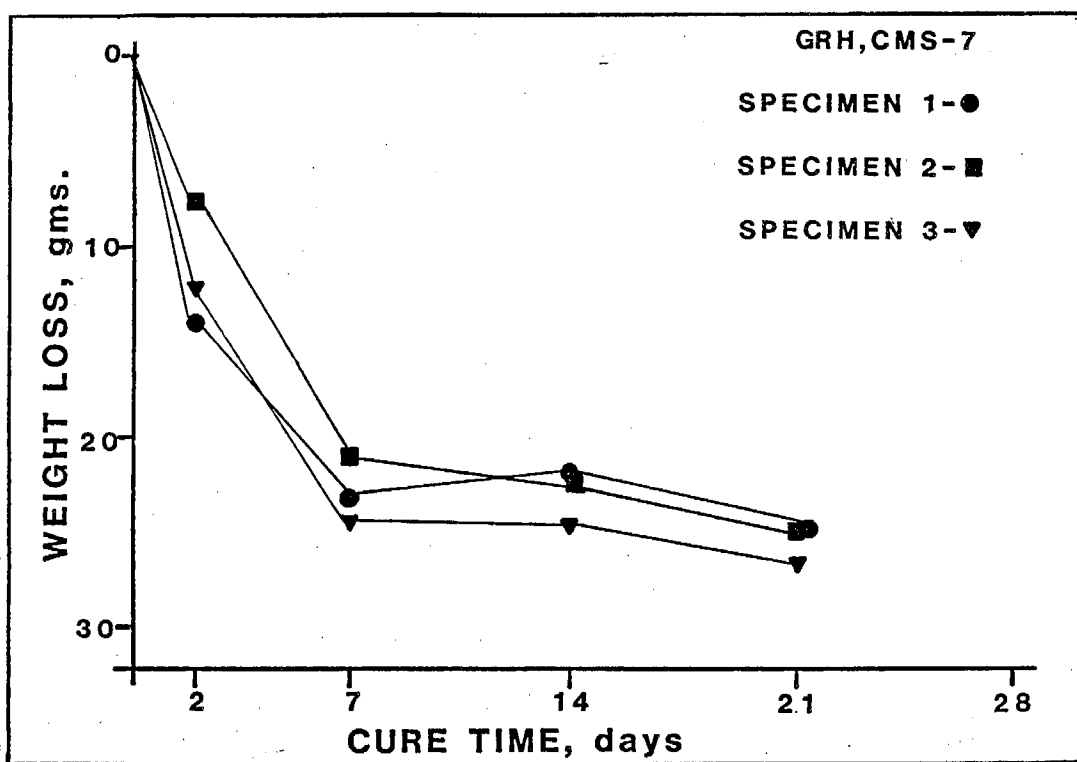


Figure 8. Weight Loss During Desiccation

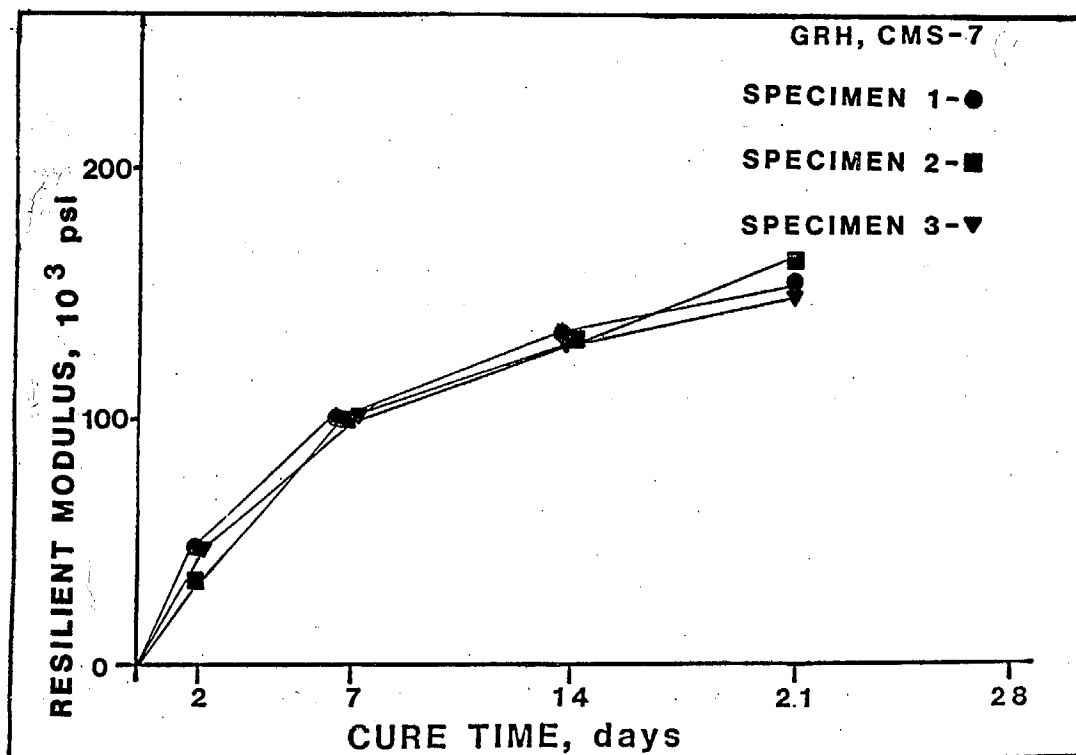


Figure 9. Resilient Modulus Gain During Desiccation

levels as differences in quality levels are in the fine (minus No. 4 mesh) fractions. For tests with the SEA emulsions, the weight of emulsion used was adjusted by ratios of specific gravities to provide volume of residue equivalent to that of an asphalt emulsion residue.

Bulk Specific Gravity. Following completion of desiccation, the bulk specific gravities of the specimens were determined in accordance with Caltrans Method of Test 308 (42).

Stabilometer. The stabilometer values of the fully desiccated specimens were determined in accordance with Caltrans Method of Test 366 (42) except that the specimens had previously been extracted from the mold and therefore were simply placed in the stabilometer device instead of being forced from the mold into the stabilometer device. Prior to testing, specimens were conditioned to 140F in a forced draft oven for 2 to 4 hours.

Cohesimeter. Following completion of the stabilometer test, the cohesimeter value of the specimens was determined at 140F in accordance with Caltrans Method of Test 306 (42).

Maximum Theoretical Specific Gravity. Following completion of cohesimeter testing, the maximum theoretical specific gravity of two specimens from each mix design at the highest emulsion residue content investigated were determined in accordance with ASTM Method of Test D2041-78 (2).

5.8 Mixture Design Calculations

The density-voids characteristics of the specimens for each mix design were determined. The procedure used follows that outlined in The Asphalt Institute Manual MS-2 (43). Computational formulas used in the analyses are:

$$G_{se} = \frac{100}{\frac{100 + P_b}{G_{mm}} - \frac{P_b}{G_b}} \quad (2)$$

$$G_{mm} = \frac{100 + P_b}{\frac{100}{G_{se}} + \frac{P_b}{G_b}} \quad (3)$$

$$P_{ba} = \frac{G_{se} - G_{sb}}{B_{sb} \times G_{se}} G_b \quad (4)$$

$$P_a = 100 \frac{G_{mm} - G_{mb}}{G_{mm}} \quad (5)$$

$$VMA = 100 - \frac{G_{mb}}{G_{sb}} \times \frac{100}{100 + P_b} \times 100 \quad (6)$$

$$P_{be} = P_b - P_{ba} \quad (7)$$

in which:

- G_{se} = effective specific gravity of the aggregate
- P_b = percent emulsion residue
- G_{mm} = maximum theoretical specific gravity determined according to ASTM D2041
- G_b = specific gravity of emulsion residue
- P_{ba} = percent absorbed emulsion residue
- G_{mb} = bulk specific gravity of specimens measured according to Caltrans 308
- G_{sb} = combined bulk specific gravity of aggregates
- P_a = percent air voids
- VMA = voids in mineral aggregate
- P_{be} = percent effective emulsion residue

The analysis procedure proceeds as follows. Using the measured maximum theoretical specific gravity (G_{mm}) of the specimens at the highest emulsion content, the aggregate effective specific gravity (G_{se}) is calculated using equation 2. Then using the calculated aggregate effective specific gravity, the maximum theoretical specific gravity of mixtures at other emulsion residue contents may be calculated using equation 3. Percent absorbed emulsion residue is calculated using equation 4, and percent air voids at each emulsion residue content calculated using equation 5. Voids in mineral aggregate at each emulsion residue content is calculated using equation 6, and the effective emulsion residue content calculated using equation 7.

Density-voids information, stabilometer values, cohesiometer values, 2 day resilient modulus, and full cure resilient modulus data are tabulated and plotted by emulsion residue content in Appendix B. Each of the two mixture design replications was calculated and plotted separately for each emulsion-aggregate combination. It is noted that for the SEA mixtures, the actual SEA residue content (weight basis) is shown as well as the asphalt residue content for an equivalent volume of asphalt emulsion residue. Differences are due to the increased specific gravity of the SEA emulsion residues as compared to the asphalt emulsion residues.

5.9 Selection of Design Emulsion Residue Content

Presently, no standardized method for selecting the design emulsion residue content for emulsified asphalt mixtures exists. For dense graded permanent surfaces, the PCD-1 manual (3) specifies a design binder content which gives a minimum of 75 percent aggregate coating, a minimum stabilometer value at 140F of 30, and a minimum cohesiometer value at 140F of 100. These criteria, however, are very general and not very restrictive. No requirements on air voids or voids in mineral aggregate are specified. Several other design methods specify minimum Marshall stability requirements, air voids, and stability losses due to soaking in water. Fong (40) discussed difficulties encountered with selection of designs for emulsified mixtures and states that no major differences were found (between available mix design methods) that would prevent predictable mixture characteristics from occurring.

The purpose of this study is to determine the feasibility of using low-solvent asphalt emulsions and sulfur-extended-asphalt emulsions with California low quality aggregates. Additionally, in order to accomplish this purpose, mixtures containing a conventional emulsion which contains solvent was studied for comparative purposes. As specified in the project RFP (1), the properties of emulsified mixtures were to conform to quality requirements of Caltrans Type B asphalt concrete (25) with a minimum stabilometer value of 30. However, for dense graded mixtures, Type B asphalt concrete requires a minimum stabilometer value of 35. Since the San Bernardino and Fresno aggregates would not meet Type B quality level requirements, properties of mixtures designed in this study were compared to Caltrans Type C asphalt concretes. Examination of data in Appendix B shows that many mixtures at varying emulsion residue contents meet requirements for dense-graded surface course emulsion mixtures as specified in PCD-1 (3). So that meaningful comparisons can be made and so that appropriate conclusions can be drawn from the data developed in this study, design emulsion residue contents which are applicable for comparable mixtures made with hot-mix asphalt for each aggregate and quality level being investigated were selected considering air voids, V.M.A., and stabilometer value variations with emulsion residue content. Data for each aggregate at each quality level with the three asphalt emulsions were considered and a design residue content selected for each aggregate at each quality level. Comparisons of mixture properties could then be made at the same residue content with the different emulsions being investigated. Use of this methodology provides a means of comparing mixture properties as affected by emulsion type without confounding analysis due to the presence of different emulsion residue contents which would result in differences in binder film thicknesses, specimen densities, air voids, and permeability by water.

Design emulsion residue contents selected for the six project aggregates are:

<u>San Bernardino</u>		<u>Fresno</u>		<u>Graniterock</u>	
<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
7.0%	7.5%	7.0%	7.5%	5.5%	6.0%

5.10 Tests on Specimens at the Design Residue Content

Following selection of the design residue contents, nine additional specimens at the design residue content for each aggregate-quality level-emulsion combination were mixed, compacted and desiccated until the full cure condition was reached (Section 5.4).

Three specimens of each mixture type were used for each of the following tests - swell, moisture vapor sensitivity, and surface abrasion. Results of these tests indicated the degree of durability of the mixtures when exposed to moisture and abrasion.

Swell. Swell tests were performed in accordance with California Method of Test 305 except that the specimens were forced back into the compaction molds prior to testing.

Moisture Vapor Susceptibility. Three specimens were subjected to the moisture vapor conditioning in accordance with Caltrans Method of Test 307. The conditioning procedure subjects the specimens to moisture vapor at 140F for 75 hours. Conditioned specimens are then tested using the stabilometer test method and the change in stabilometer value (as compared to the dry, unconditioned result) used to determine the degree to which the specimens were affected by the moisture vapor conditioning procedure. In variance with the test method (Caltrans 307), the specimens were forced into the compaction molds prior to moisture conditioning. Additionally, cohesiometer tests (Caltrans 306) were performed on the conditioned specimens immediately after completion of stabilometer testing.

Surface Abrasion. Surface abrasion tests were performed on the fully cured specimens by the Caltrans Materials Laboratory in Sacramento, California in accordance with Caltrans Method of Test 360 using Method B except that the specimens were compacted and then desiccated using procedures contained in Sections 5.5 and 5.6. Since the compacted specimens were greater than 2 inches in thickness (as specified by the test method), they were sawn to the appropriate thickness using a diamond saw. The surface abrasion test is designed to indicate the ability of a compacted mixture to resist surface abrasion or raveling in the presence of water when

subjected to abrasion from snow tire chains (42). Testing consists of soaking top surface of the specimen in the mold in water at room temperature for 20 hours, temperature conditioning at 40F, placing 8 steel balls and 40F water on top of the specimen (inside the mold), and then placing the specimen in the abrasion device and shaking vertically at 1200 cycles per minute for 15 minutes using a 1 inch stroke. Weight loss of the specimens due to abrasion from the steel balls is determined in grams and recorded as the surface abrasion result.

6.0 RESULTS AND DISCUSSION, ASPHALT EMULSION EXPERIMENT

6.1 Emulsions Compatability During Mixing

Percent aggregate coating during mixing at design residue contents data are tabulated in Appendix C in Table C1 and the ANOVA summary in Table C2. ANOVA shows that emulsion, aggregate and the emulsion-aggregate interaction are significant effects at the 99 percent confidence level. Aggregate quality level is significant at the 95 percent level. Other interactions are not significant at the 95 percent level. Data means are plotted in Figure C1 and the Newman-Keuls ranking is shown in Figure C2. Ranking of means shows that for all aggregates at both quality levels, the CSS-0 emulsion gave the best coating, followed by the CMS-0 and then by the CMS-7 emulsion. With SBL, FL, GRH, and GRL aggregates statistical differences were not noted between coatings when using the CSS-0 and CMS-0 emulsions. With SBH aggregate, no differences in coating were noted between the three emulsions. For FH aggregate, no differences were noted in coating between the CMS-0 and CMS-7 emulsions. These results indicate that the CSS-0 (90% average coating) and CMS-0 (82.7% average coating) emulsion coated aggregates considerably better than the CMS-7 (67.2% average coating) emulsion and that the CMS-0 and CSS-0 resulted in approximately the same degree of coating.

6.2 Film Stripping

Film stripping data are tabulated in Appendix C in Table C3 and the ANOVA summary in Table C4. Two-way ANOVA (26) was performed on the data as the tests are performed only on the coarse (plus No. 4 mesh) material thus, aggregate quality level is not a subclassification. ANOVA shows that aggregate is a significant effect at the 95 percent confidence level and that emulsion and the emulsion-aggregate interaction are not significant effects at the 95 percent confidence level. Data means are plotted in Figure C3 and the Newman-Keuls ranking is shown in Figure C4. The ranking also shows that no statistical differences exist in film stripping results by emulsion type (this is also indicated by the ANOVA). Mean results of percent stripped surface are higher for Fresno aggregate (5.3%) than for Graniterock (1.2%) or San Bernardino aggregate (1.7%) for each of the three emulsions.

6.3 Initial Resilient Modulus

Initial resilient modulus (2 day) data at the design binder contents are tabulated in Appendix C in Table C5 and ANOVA summary in Table C6. ANOVA shows that all main effects and interactions except the aggregate-quality level interaction are significant effects at the 99 percent confidence level. The aggregate-quality level interaction is not significant at the 95 percent confidence level. Data means are plotted in Figure C5 and the Newman-Keuls ranking is shown in Figure C6. Ranking of means shows for each aggregate-quality level combination investigated, that the initial resilient modulus of specimens containing the CSS-0 and CMS-0 emulsions were not significantly different and were statistically higher than moduli of specimens containing the CMS-7 emulsion. Average 2 day modulus for specimens containing the CSS-0 and CMS-0 emulsions is 161,000 psi compared to 60,000 psi for specimens containing the CMS-7 emulsion. These results indicate that specimens containing the CSS and CMS solvent free emulsions have higher early strength than specimens containing the CMS-7 emulsion for all aggregates and quality levels investigated.

6.4 Full Cure Resilient Modulus

Resilient modulus data at the design binder contents after completion of desiccation (full cure) are tabulated in Appendix C in Table C7 and the ANOVA summary in Table C8. ANOVA shows that emulsion type and aggregate quality level are significant effects at the 99 percent confidence level. Aggregate is a significant effect at the 95 percent confidence level. All interactions are not significant effects at the 95 percent confidence level. Data means are plotted in Figure C7 and the Newman-Keuls ranking is shown in Figure C8. Ranking of data means shows that for each aggregate-quality level combination investigated, that the final cure resilient modulus of specimens containing the CSS-0 and CMS-0 emulsions were not significantly different and were higher than moduli of specimens containing the CMS-7 emulsion. Average full cure modulus for specimens containing the CSS-0 and CMS-0 emulsions is 308,000 psi compared to 96,000 psi for specimens containing the CMS-7 emulsion. These results show that specimens containing the CSS-0 and CMS-0 emulsions have higher full cure moduli than specimens containing

the CMS-7 emulsion for all aggregates and quality levels investigated. Additionally, specimens containing the CSS-0 and CMS-0 emulsions have higher moduli at 2 days of curing in air than specimens containing the CMS-7 emulsion have after fully curing using the vacuum desiccation technique. (See Section 6.3).

6.5 Density

Density data at the design binder content are tabulated in Appendix C in Table C9 and the ANOVA summary in Table C10. ANOVA shows that emulsion type, aggregate, and quality level are significant effects at the 99 percent confidence level. All interactions are not significant at the 95 percent confidence level. Data means are plotted in Figure C9 and the Newman-Keuls ranking shown in Figure C10. Ranking of data means shows that for specimens containing SBH, SBL, and GRH aggregate, densities obtained using the CSS-0 and CMS-7 emulsions were not different and were higher than densities obtained for the CMS-0 emulsion. For FH, FL, and GRH aggregates, densities obtained for specimens containing the different emulsions were significantly different. With these latter aggregates, use of the CMS-7 emulsion resulted in the highest density, followed by the CSS-0 and then the CMS-0 emulsion. Specimens containing Graniterock aggregate had higher densities than specimens containing San Bernardino or Fresno aggregate. This is due to the higher aggregate specific gravity of the Graniterock aggregate as compared to the San Bernardino or Fresno aggregate. Results indicate that for all aggregates at each quality level, highest degrees of compaction were obtained with the CMS-7 emulsion followed by the CSS-0 and then the CMS-0 emulsion. These differences are theorized to be related to 2 factors. First, the CMS-7 emulsion residue is much softer than either the CSS-0 or CMS-0 due to the presence of solvent and thus allows greater compaction to occur with a given compactive effort than with the solvent free emulsions. (See results in Section 3.4). Second, with the solvent free emulsions, the lesser densities obtained with the CMS-0 emulsion as compared to the CSS-0 emulsion are believed due to the medium setting characteristics of the CMS-0 emulsion compared to slow setting characteristics of the CSS-0 emulsion. This results in a stiffer binder in a shorter period for the CMS-0 emulsion

than for the CSS-0 emulsion. Utilization of a higher fluid at compaction content with the CMS-0 emulsion to attempted to reduce binder stiffness at compaction would not increase densities obtained due to the presence of more fluids in the mix voids which would limit the degree of compaction attained.

6.6 Air Voids

Air voids data at the design binder contents are tabulated in Appendix C in Table C11 and the ANOVA summary in Table C12. ANOVA shows that emulsion type and aggregate quality level are significant effects at the 99 percent confidence level. Aggregate type is significant at the 95 percent confidence level. All interactions are not significant at the 95 percent confidence level. Data means are plotted in Figure C11 and the Newman-Keuls ranking of data is shown in Figure C12. The ranking shows for each emulsion-quality level investigated that specimens containing the CMS-0 emulsion had the highest mean air voids content, followed by the CSS-0 emulsion and then the CMS 7 emulsion. For all aggregate-quality level combinations except SBL, air voids data at design binder contents were not different for specimens containing the CMS-0 and CSS-0 emulsions. For all combinations except FH and GRL, results for the CSS-0 and CMS-7 emulsions were not different. Average air voids were 9.0 percent for specimens containing the CMS-0 emulsions 7.8 percent for those containing the CSS-0 emulsion, and 6.5 percent for the CMS-7 emulsion. These results are compatible with the trends in degree of compaction attained as indicated by density results (Section 6.5).

6.7 Stabilometer Values

Stabilometer value data are tabulated in Appendix C in Table C13 and the ANOVA summary in Table C14. ANOVA shows that emulsion type, aggregate type, quality level, the emulsion-aggregate interaction and the aggregate-quality level interaction are significant effects at the 99 percent confidence level. The emulsion-quality level interaction is significant at the 95 percent confidence level and the three-way interaction is not significant at the 95 percent level. Data means are plotted in Figure C13 and the Newman-Keuls ranking is shown in Figure C14.

The ranking shows that for SBH, SBL, FH, and FL aggregates, stabilometer values for specimens containing CSS-0 and CMS-0 emulsions are not significantly different and are higher than for specimens containing the CMS-7 emulsion. For the GRH and GRL aggregates, significant differences in stabilometer values for specimens containing the different emulsions were not noted. With the CSS-0 and CMS-0 emulsions, Fresno aggregate had the highest stabilometer value (36.2 average). With each mixture combination except for the CMS-0 emulsion with Fresno aggregate, the low quality level specimens had lower stabilometer values than high quality level aggregate for each emulsion. Several of the aggregate-emulsion combinations at the design binder contents exceeded the minimum stabilometer value of 30 specified for Type C asphalt concrete by Caltrans.

Examination of data in Appendix B shows that for several of the mixture combinations investigated which did not meet the minimum stabilometer value of 30, reductions in emulsion residue contents would result in specimens with stabilometer values greater than 30. According to the PCD-1 (3) mixture design criteria, these specimens at reduced emulsion contents would be acceptable.

6.8 Cohesiometer Value

Cohesiometer data are tabulated in Appendix C in Table C15 and the ANOVA summary in Table C16. ANOVA shows that emulsion type, aggregate, and aggregate quality level are significant effects at the 99 percent confidence level. The emulsion-aggregate interaction and the aggregate-quality level interaction are significant effects at the 95 percent level. Other interactions are not significant at the 95 percent level. Data means are plotted in Figure C15 and the Newman-Keuls ranking is shown in Figure C16. The ranking shows that for SBH, SBL, FL, and GRH aggregates, cohesiometer values for specimens containing CMS-0 and CSS-0 emulsions are not significantly different and are higher than for specimens containing the CMS-7 emulsion. For FH and GRL aggregate, cohesiometer values were not significantly different for the three emulsions. Additionally, for the GRH aggregate, cohesiometer values for the CMS-0 and CMS-7 emulsions were not significantly

different. Average cohesiometer value for all specimens containing the CSS-0 and CMS-0 emulsions was 288 compared to 160 for those containing the CMS-7 emulsion. For all aggregate-emulsion combinations investigated, the low quality level aggregate resulted in higher mean cohesiometer values than the high quality aggregates.

6.9 Swell

Swell test expansion data are tabulated in Appendix C in Table C17 and the ANOVA summary in Table C18. ANOVA shows that all main effects and interactions are significant effects at the 99 percent confidence level. Data means are plotted in Figure C17 and the Newman-Keuls ranking in Figure C18. The ranking shows that for SBH, SBL, FH, and FL aggregate, specimens containing the CMS-0 emulsion swelled to a greater degree than specimens containing the CSS-0 or CMS-7 emulsions. The Caltrans asphalt concrete specification maximum for swell is 0.030 inches (25). Swells of SBL and FL with the CMS-0 emulsion exceeded this limit. With SBH, SBL, and FH, significant differences in swell between specimens containing the CSS-0 and CMS-7 emulsions were not noted. With both Graniterock aggregates, no difference in swells of specimens containing the 3 emulsions were noted (average swell of 0.000 inches). These results indicate that with both low and high quality aggregates use of the CMS-7 emulsion resulted in, for all practical purposes, specimens which do not swell. With lower quality aggregates (SBL, FL), use of the solvent free emulsions (especially the CMS-0) resulted in higher amounts of swell which were in excess of specification requirements for asphalt concrete. With better quality aggregates, (SBH, GRH, and GRL) emulsion type did not significantly influence swell.

6.10 MVS Conditioned Stabilometer Value

Stabilometer values after the MVS conditioning procedure are tabulated in Appendix C in Table C19 and the ANOVA summary in Table C20. ANOVA shows that all main effects and the emulsion-aggregate interaction are significant effects at the 99 percent confidence level. The emulsion-aggregate quality level interaction is significant at the 95 percent

level. Other interactions are not significant effects at the 95 percent confidence level. Data means are plotted in Figure C19 and the Newman-Keuls ranking is shown in Figure C20. The ranking shows for SBH, SBL, and FL aggregates, that there are no significant differences between MVS conditioned stabilometer values of specimens containing the three emulsions. Several other similarities are noted. The Caltrans specification minimum MVS conditioned stabilometer value for Type C asphalt concrete is 20 (25). With the CSS-0 emulsion, SBH, FH, and GRH aggregate met the requirement. With the CMS-0, only GRH aggregate met the requirement and with the CMS-7 emulsion, SBH, GRH, and GRL aggregate had MVS conditioned stabilometer values in excess of 20.

The percentage of the original stabilometer value retained after MVS conditioning is tabulated in Table 23. Average percent retention (for all aggregates) for CSS-0 emulsion is 58.1 percent, for CMS-0 emulsion, 44.7 percent, and for the CMS-7 emulsion, 87.8 percent. These values show that the use of the CMS-7 emulsion resulted in a greater percent retention of original stabilometer value than with the CSS-0 and CMS-0 emulsions. These results may, however, be influenced by the air voids levels of the specimens. Increased air voids levels have been found to decrease moisture resistance of asphalt pavements (29, 30, 31). For all aggregates investigated, specimens containing CMS-7 emulsion had the lowest air voids, CSS-0 specimens the second lowest, and CMS-0 specimens, the highest.

Figure 10 is a plot of air voids at the design binder content as a function of the percent retained stabilometer value after MVS conditioning. Linear regression (26) performed on data for high quality level aggregates (SBH, FH, and GRH with each emulsion shows a correlation coefficient (r^2 value) of 0.78, and for low quality level aggregates, 0.49. Thus it appears that air void levels are correlated with retained stabilometer for specimens containing high quality aggregate to a greater degree than for those containing low quality aggregate.

Table 23

PERCENTAGE OF STABILOMETER VALUE
RETAINED AFTER MVS CONDITIONING

Emulsion	San Bernardino		Fresno		Graniterock	
	High	Low	High	Low	High	Low
CSS-0	70.6	51.9	66.4	29.5	95.6	34.7
CMS-0	50.5	34.5	34.2	21.7	63.1	64.2
CMS-7	91.5	113.6	87.9	50.3	96.6	86.8

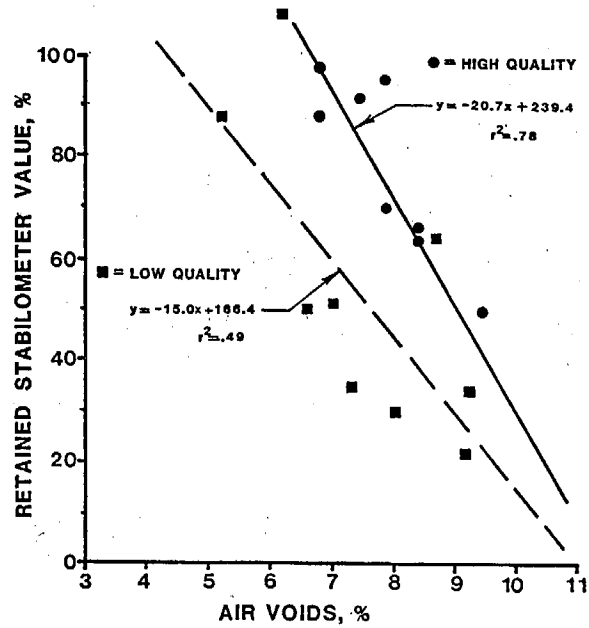


Figure 10. Percent Retained Stability As A Function Of Air Voids For Asphalt Emulsions Experiment

6.11 MVS Conditioned Cohesimeter Value

Cohesimeter value data obtained after MVS conditioning are tabulated in Appendix C in Table C21 and the ANOVA summary in Table C22. ANOVA shows that emulsion is a significant effect at the 95 percent confidence level and that other main effects and interactions are not significant. Data means are plotted in Figure C21 and the Newman-Keuls ranking in Figure C22. The ranking shows for all aggregates except FH, that cohesimeter values of specimens containing the three emulsions were not significantly different. For FH specimens, differences were not noted with the CMS-7 and CSS-0 emulsions, or for the CSS-0 and CMS-0 emulsions. Average MVS conditioned average cohesimeter value for all specimens was 107.

6.12 Surface Abrasion

Surface abrasion data are tabulated in Appendix C in Table C23 and the ANOVA summary in Table C24. ANOVA shows that emulsion, aggregate, the aggregate-quality level interaction, and the three-way interaction are significant effects at the 99 percent confidence level. Aggregate quality level and other interactions are significant at the 95 percent confidence level. Data means are plotted in Figure C23 and the Newman-Keuls ranking in Figure C24. The ranking shows that for SBH and GRH aggregate, surface abrasion results of specimens with the three emulsions were not significantly different. Several differences in results were noted for other aggregates. Specimens containing the CMS-7 emulsion had the lowest amount of surface abrasion (43.6 gram average for all aggregates).

Specimens containing the CSS-0 emulsion had an average loss of (82.5 gram), and those containing the CMS-0 emulsion had the largest loss (129.3 gram average). Additionally, the lower quality aggregates (SBL, FH, and FL) tended to have higher surface abrasion values than higher quality aggregates (SBH, GRH, and GRL). Higher abrasion losses for specimens containing the CSS-0 and CMS-0 emulsions than for those containing the CMS-7 emulsion may be related to the softer residue of the CMS-7 emulsion as compared to those of the CSS-0 and CMS-0 emulsions. (See Section 3.4). The softer residue of

the CMS-7 emulsion would have a lower tendency to fracture on impact at the test temperature (40F) than the stiffer residues of the CSS-0 and CMS-0 emulsions. Currently, no specification maximum abrasion loss is available for the surface abrasion test. However, communications with Caltrans personnel have indicated that a maximum loss of 35 grams is being considered as a maximum limit. For the mixtures tested, only specimens containing the GRH and GRL aggregate with the CMS-7 emulsion met this condition.

7.0 RESULTS AND DISCUSSION, SULFUR-EXTENDED-ASPHALT EMULSION EXPERIMENT

7.1 Emulsion Compatability During Mixing

Percent aggregate coating during mixing at design residue contents data are tabulated in Appendix D in Table D1 and the ANOVA summary in Table D2. ANOVA shows that all main effects and the emulsion-aggregate interaction are significant effects at the 99 percent confidence level. Other interactions are not significant effects at the 95 percent confidence level. Data means are plotted in Figure D1 and the Newman-Keuls ranking in Figure D2. Ranking of the data shows that both SEA emulsions gave higher mean percentage coatings than did the CMS-7 emulsion for all aggregates. Also, for all aggregates, significant differences in percent coating were not noted between the two SEA emulsion (average percent coating for SS-15 and SS-30 emulsions of 81.2 percent). Average coating for the CMS-7 emulsion was 67.2 percent.

7.2 Film Stripping

Film stripping data are tabulated in Appendix D in Table D3 and the ANOVA summary in Table D4. ANOVA shows that emulsion is a significant effect at the 99 percent confidence level and that aggregate and the emulsion-aggregate interaction are significant at the 95 percent level. Data means are plotted in Figure D3 and the Newman-Keuls ranking is shown in Figure D4. The ranking shows for San Bernardino aggregate that both SEA emulsions had significantly higher film stripping percentages (23.8% average) than the CMS-7 emulsion (0.0%).

For Fresno aggregate, the SS-15 emulsion experienced the highest amount of film stripping (25.0%) followed by CMS-7 and the SS-30 which were not significantly different (1.3% average). The same ranking order is noted for Graniterock aggregate.

7.3 Initial Resilient Modulus

Initial resilient modulus (2 day) data at the design binder contents are tabulated in Appendix D in Table D5 and the ANOVA summary in Table D6. ANOVA shows that all main effects and the emulsion-aggregate interaction are significant effects at the 99 percent confidence level. The emulsion-aggregate quality level interaction is significant at the 95 percent confidence level and other interactions are not significant. Data means are plotted in Figure D5 and the Newman-Keuls ranking in Figure D6. The ranking shows that for all aggregates, specimens containing the SS-30 emulsion had the highest modulus (187,000 psi average), followed by the SS-15 emulsion (155,000 psi average), and then by specimens containing the CMS-7 emulsion (60,000 psi average). For SBH, FH, and FL aggregate, statistically significant differences between initial modulus of specimens containing SS-15 and SS-30 emulsions were not noted.

7.4 Full Cure Resilient Modulus

Resilient modulus data at the design binder content after completion of desiccation (full cure) are tabulated in Appendix D in Table D7 and the ANOVA summary in Table D8. ANOVA shows that emulsion is a significant effect at the 99 percent confidence level and that aggregate is significant at the 95 percent level. Aggregate quality level and all interactions are not significant effects. Data means are plotted in Figure D7 and the Newman-Keuls ranking in Figure D8. The ranking shows that for all aggregates, no significant differences exist in moduli of specimens containing the SS-15 and SS-30 emulsions (318,000 psi average). Specimens containing the SS-15 and SS-30 emulsions had significantly higher moduli than specimens containing the CMS-7 emulsion (96,000 psi average) for all aggregates.

7.5 Density

Density data at the design binder content are tabulated in Appendix D in Table D9 and the ANOVA summary in Table D10. ANOVA shows that emulsion, aggregate, quality level, the emulsion-quality level interaction and the three-way interaction are significant effects at the 99 percent confidence level.

Other interactions are not significant. Data means are plotted in Figure D9 and the Newman-Keuls ranking in Figure D10. The ranking shows that for each aggregate specimens containing the SS-15 emulsions had the lowest densities. For SBH, FH, FL, and GRH, significant differences in densities were not noted for specimens containing the CMS-7 and SS-30 emulsion.

7.6 Air Voids

Air voids data at the design binder content are tabulated in Appendix D in Table D11 and the ANOVA summary in Table D12. ANOVA shows that emulsion and aggregate are significant effects at the 99 percent confidence level. Aggregate quality level is significant at the 95 percent confidence level and all interactions are not significant effects. Data means are plotted in Figure D11 and the Newman-Keuls ranking in Figure D12. The ranking shows that for all aggregates except GRH specimens containing CMS-7 emulsion had the lowest percent air voids. For all aggregates except GRH, differences in air voids levels of specimens containing SS-15 and SS-30 emulsion were not noted. Average air voids for specimens containing the SS-15 and SS-30 emulsions, for all aggregates is 8.8 percent compared to an average of 6.5 percent for specimens containing CMS-7 emulsion. These results indicate that higher degrees of compaction may be attained for a given comparative effect with the CMS-7 emulsion than for the SS-15 and SS-30 SEA emulsions. This may be due to the more viscous residue of the SEA emulsions as compared to residue from the CMS-7 emulsion (Sections 3.4 and 3.5).

7.7 Stabilometer Values

Stabilometer value data are tabulated in Appendix D in Table D13 and the ANOVA summary in Table D14. ANOVA shows that emulsion, aggregate quality level, and the emulsion-aggregate interaction are significant effects at the 99 percent confidence level. Aggregate and other interactions are not significant effects. Data means are plotted in Figure D13 and the Newman-Keuls ranking in Figure D14. Ranking of the data shows for SBH, SBL, FH, and FL aggregates, that stabilometer values of specimens containing the SS-15 and SS-30 SEA emulsions were not significantly

different and were higher than for those containing the CMS-7 emulsion. Average stabilometer value for specimens containing SBH, SBL, FH, and FL aggregate with the SS-15 and SS-30 SEA emulsions was 37.7 compared to 19.0 for those containing the CMS-7 emulsion. For GRH and GRL aggregates, no significant differences in stabilometer values of specimens containing the SS-15, SS-30, or CMS-7 emulsions were noted. (32.2 average for GRH and 26.0 average for GRL).

7.8 Cohesiometer Value

Cohesiometer value data are tabulated in Appendix D in Table D15 and the ANOVA summary in Table D16. ANOVA shows that aggregate quality level is a significant effect at the 95 percent confidence level. All other main effects and interactions are not significant. Data means are plotted in Figure D15 and the Newman-Keuls ranking in Figure D16. The ranking shows that for all aggregates except SBH, that no differences in cohesiometer values exist for specimens containing the three emulsions. Average cohesiometer value for all mixtures except those containing SBH aggregate is 170. For SBH aggregate, specimens containing the SS-30 emulsion had the highest cohesiometer value (268), while the cohesiometer values of specimens containing CMS-7 and SS-15 emulsion were lower and not significantly different (72 average).

7.9 Swell

Swell test expansion data are tabulated in Appendix D in Table D17 and the ANOVA summary in Table D18. In order to comply with variance homogeneity constraints, square root transformations of data were required prior to analysis. ANOVA shows that all main effects and interactions are significant effects at the 99 percent confidence level. Data means are plotted in Figure D17 and the Newman-Keuls ranking in Figure D18. The ranking shows that specimens containing the SS-15 and SS-30 SEA emulsions had higher values with SBH, SBL, FH, and FL aggregates than specimens containing CMS-7 emulsion. Average swell with these aggregates for specimens containing the SS-15 and SS-30 emulsions is .034 inch compared to .001 inch for specimens containing

the CMS-7 emulsion. With GRH and GRL aggregates, lesser differences in swell results were noted - .004 inch average for specimens containing the SS-15 and SS-30 SEA emulsion compared to 0.000 inches for those containing the CMS-7 emulsion.

7.10 MVS Conditioned Stabilometer Value

Stabilometer values after MVS conditioning are tabulated in Appendix D in Table D19 and the ANOVA summary in Table D20. ANOVA shows that all main effects and interactions are significant at the 99 percent confidence level except for the emulsion-aggregate quality level and three-way interaction which are not significant at the 95 percent confidence level. Data means are plotted in Figure D19 and the Newman-Keuls ranking is Figure D20. The ranking shows for all aggregates except FL that specimens containing the CMS-7 emulsion had the highest stabilometer value after MVS conditioning. Many similarities and differences in data are noted in the ranking (Figure D20). Generally, specimens containing the SS-15 and SS-30 emulsions had lower MVS conditioned stabilometer values than CMS-7 specimens. The Caltrans specification minimum MVS conditioned stabilometer value for Type C asphalt concrete is 20. With the SS-15 emulsion, FL and GRH aggregate met this requirement. With the SS-30 emulsion, only GRH aggregate met the minimum value of 20.

With the CMS-7 emulsion, SBH, GRH, and GRL aggregate had MVS conditioned stabilometer values in excess of 20. The percentage of the original stabilometer value retained after MVS conditioning is tabulated in Table 24. Average percent retention (for all aggregates) for SS-15 emulsion is 43.4 percent, for SS-30 emulsion, 36.4 percent, and for CMS-7 emulsion, 87.8 percent. These values indicate that the use of CMS-7 emulsion results in greater retention of stabilometer value after MVS conditioning. As discussed in Section 6.10 of this report, these results may be influenced by air voids levels as higher air voids in the lab compacted specimens were attained for the SS-15 and SS-30 emulsions than for the CMS-7.

Table 24

PERCENTAGE OF STABILOMETER VALUE
RETAINED AFTER MVS CONDITIONING (SEA EXPERIMENT)

Emulsion	San Bernardino		Fresno		Graniterock	
	High	Low	High	Low	High	Low
SS-15 SEA	30.9	16.7	43.5	49.0	72.8	47.2
SS-30 SEA	33.5	30.8	22.0	19.0	71.3	21.7
CMS-7	91.5	113.6	87.9	50.3	96.6	86.8

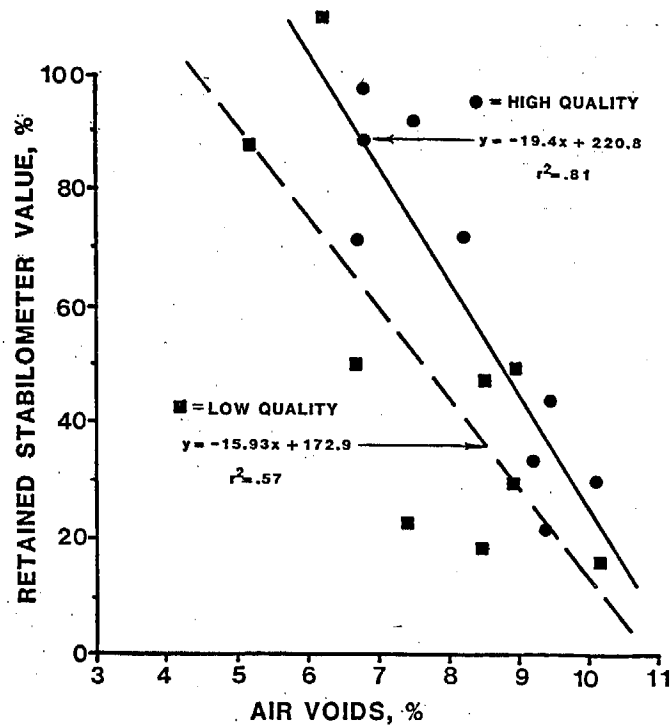


Figure 11. Percent Retained Stability As A Function Of Air Voids For SEA Emulsion Experiment

Figure 11 is a plot of air voids at the design binder content against percent retained stabilometer value after MVS conditioning. Linear regression (26) showed a correlation coefficients of 0.82 for aggregates at the high quality level and 0.65 at the low quality level. Thus it appears that air voids levels are correlated with percent retained stabilometer value after MVS conditioning to a greater degree with the high quality aggregates than with low quality aggregates.

7.11 MVS Conditioned Cohesimeter Value

Cohesimeter values after MVS conditioning are tabulated in Appendix D in Table D21 and the ANOVA summary in Table D22. Several specimens were too weak to test (TWT) in the cohesimeter after MVS conditioning as indicated in Table D21. For ANOVA purposes, cohesimeter values of 0 were assigned for these specimens. ANOVA shows that aggregate, aggregate quality level, and the emulsion-aggregate interaction are significant effects at the 99 percent confidence level. Emulsion and the emulsion-aggregate quality level interaction are significant effects at the 95 percent confidence level. Other interactions are not significant at the 95 percent confidence level. Data means are plotted in Figure D21 and the Newman-Keuls ranking is shown in Figure D22. The ranking shows that with SBH, FH, GRH, and GRL aggregate, cohesimeter values of specimens containing the three emulsions are not significantly different. With SBL aggregate, results for CMS-7 and SS-30 emulsion were not different and the SS-15 emulsion specimens were too weak to test. For FH aggregate, results for CMS-7 and SS-15 emulsions were not different and the SS-30 specimens were too weak to test. Average MVS conditioned cohesimeter value for all specimens was 105.

7.12 Surface Abrasion

Surface abrasion test results are tabulated in Appendix D in Table D23. During testing, several sets of specimens swelled or disintegrated yielding no result. Therefore, ANOVA could not be performed on the data. Data means are plotted in Figure D23. Examination of data shows that specimens containing SBH and SBL aggregate with both SEA emulsions either swelled and could not be tested or disintegrated during testing. Surface abrasion losses for both

Fresno aggregates were higher with the SEA emulsions than with the CMS-7 emulsion. For GRH aggregate, losses for specimens containing the SEA emulsions (58.0 gram average) were higher than for the specimens containing the CMS-7 emulsion (31.9 gram). For GRL aggregate, greater difference in results is noted. None of the specimens containing the SEA emulsions met the proposed Caltrans abrasion loss limit of 35 grams maximum loss.

8.0 PAVEMENT STRUCTURAL DESIGNS

In order to provide an indication of the economics of using the mixtures being investigated in this study, pavement structural designs were performed for each mixture investigated using mixture properties at the design emulsion residue content. Structural sections were designed using the method contained in the PCD-1 (3) manual. This method determines the required thickness of full depth emulsified asphalt paving mixture placed directly on properly prepared subgrade soils. The design procedure is based on providing sufficient pavement thickness such that the horizontal tensile strain at the bottom of emulsified mixture and the vertical compressive strain at the surface of the subgrade are limited to values which will maximize resistance to fatigue cracking and will minimize surface rutting (3).

For purposes of this study, pavement structural designs were performed for two different traffic levels, two subgrade modulus levels, and two climatic conditions yielding eight different sets of typical conditions. Design traffic levels considered were 10,000 and 100,000 equivalent 18 kip axle loadings (EAL's) for a 20 year design life. These levels would be typical of low volume roadways. The two subgrades strength levels considered were subgrades with modulus values of 6,000 psi and 30,000 psi which are representative of subgrades with California Bearing Ratios (CBR) of approximately 4 and 20 (3).

The two climatic conditions considered were areas with mean annual air temperatures (MAAT) of 55 to 65F (typical of Sacramento) and greater than 65F (typical of Bakersfield (3)). Based on evapotranspiration potential, emulsion cure times of 1 year were assumed for both climates (3).

The PCD-1 pavement structural design method for emulsified asphalts consists of first determining the required section thickness based on the specific set of conditions and mixture full cure modulus to satisfy tensile strain requirements. Table E1 in Appendix E which was obtained from the PCD-1 manual (3), is used for this determination. Since fatigue characteristics of mixtures with differing binder and air void levels differ (3), adjustments to the thickness determined

from Table E1, for the specific mixture being investigated are required. This adjustment is made by computing the ratio of the binder volume divided by the air void plus binder volume of the specific mixture, and then using Figure E1 to determine the corrected thickness required to satisfy tensile strain requirements for the specific mixture.

Table E2 is used to compute the pavement section thickness required to satisfy subgrade compressive strain requirements, for the specific set of conditions and mixture full cure modulus being considered. The design procedure calls for a check on thickness to satisfy subgrade compressive strain requirements at an early mixture cure condition assuming a mixture modulus of 50,000 psi. Since the early cure (2 day) modulus of all of the solvent free and SEA mixtures was in excess of 50,000 psi, thickness requirements for this condition were not evaluated in the designs.

Figures E2 through E5 in Appendix E are plots of thickness requirements for tensile strain as a function of mixture modulus for the climatic, subgrade, and traffic conditions considered. Similarly, Figures E6 through E9 are plots of required thickness to satisfy subgrade strain requirements as a function of mixture full cure modulus for the conditions considered. Tables E3 through E10 contain required thicknesses to satisfy mixture tensile strain and subgrade compressive strain requirements for each aggregate-quality level-emulsion combination investigated in this study. Summaries of the design thicknesses for each set of conditions investigated are tabulated in Tables 25 through 32. The designs summarized in Tables 25 through 32 show for all subgrade, environmental and traffic conditions considered, that required section thicknesses for mixtures containing the CSS-0, CMS-0, SS-15, and SS-30 emulsions are approximately the same (generally within 0.5 inch), while thicknesses required for mixtures containing the CMS-7 emulsion are greater (generally between 2 and 3 inches greater) than for the others. These results indicate that lesser pavement thicknesses are required when using the CSS-0, CMS-0, SS-15, or SS-30 emulsions when compared to the CMS-7 emulsion.

For the pavement design method used, pavement sections are selected considering mixture resilient modulus, air voids and binder volumes. Most pavement section design methods available consider at the most modulus and fatigue characteristics. A standard procedure which considers factors such as aggregate gradation, sand equivalent, stabilometer value, MVS characteristics, etc. is not available. These characteristics (especially moisture resistance) may (depending on local environmental conditions) and probably do influence the performance of pavements and should be considered in the design procedure. These factors should be considered based on local conditions and experience.

The reason for lessor thickness being required for low quality than for high quality mixes is that for nearly all mixes the low quality level produced higher resilient modulus values. Since modulus is the major material input in the design procedure, it has a large effect on the design thickness.

Table 25

Design Thickness, inches:

$$E_s = 6000 \text{ psi}, EAL = 1 \times 10^4 \text{ MAAT} = 55-65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	4.3	4.3	4.3	4.3	4.3	4.3
CMS-0	4.3	4.3	4.3	4.3	4.3	4.3
CMS-7	6.0	4.5	5.3	4.5	5.4	4.6
SS-15	4.3	4.3	4.3	4.3	4.3	4.3
SS-30	4.3	4.3	4.3	4.3	4.3	4.3

Table 26

Design Thickness, inches:

$$E_s = 6000 \text{ psi}, EAL = 1 \times 10^5 \text{ MAAT} = 55-65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	7.4	6.8	6.8	6.8	7.0	6.8
CMS-0	8.0	7.5	7.8	7.2	7.8	7.0
CMS-7	10.7	8.8	10.4	8.5	10.2	8.1
SS-15	7.8	7.6	7.2	7.2	7.3	7.0
SS-30	7.4	7.1	7.2	6.8	6.8	6.8

Table 27

Design Thickness, inches:

$$E_s = 6000 \text{ psi}, EAL = 1 \times 10^4 \text{ MAAT} > 65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	4.6	4.3	4.3	4.3	4.5	4.3
CMS-0	4.8	4.6	4.7	4.3	4.6	4.3
CMS-7	6.8	6.4	6.8	6.2	6.7	6.2
SS-15	5.0	4.8	4.5	4.3	4.4	4.5
SS-30	4.5	4.3	4.4	4.3	4.3	4.3

Table 28

Design Thickness, inches:

$$E_s = 6000 \text{ psi}, EAL = 1 \times 10^5 \text{ MAAT} > 65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	8.7	7.4	8.1	7.7	9.0	7.7
CMS-0	9.4	9.0	9.2	8.7	9.1	8.5
CMS-7	11.8	9.8	11.1	9.5	11.9	9.3
SS-15	9.4	9.4	8.8	8.4	8.7	8.4
SS-30	9.0	8.6	8.7	8.2	7.8	7.8

Table 29

Design Thickness, inches:

$$E_s = 30,000 \text{ psi}, EAL = 1 \times 10^4 \text{ MAAT} = 55-65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	2.5	2.5	2.5	2.5	2.5	2.5
CMS-0	2.5	2.5	2.5	2.5	2.5	2.5
CMS-7	3.1	2.9	3.1	2.8	3.0	2.8
SS-15	2.6	2.5	2.6	2.5	2.5	2.5
SS-30	2.5	2.5	2.5	2.5	2.5	2.5

Table 30

Design Thickness, inches:

$$E_s = 30,000 \text{ psi}, EAL = 1 \times 10^5 \text{ MAAT} = 55-65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	3.2	2.9	2.9	2.9	3.1	2.9
CMS-0	3.1	3.0	3.0	2.9	3.0	2.9
CMS-7	5.3	4.5	5.3	4.3	4.9	4.3
SS-15	2.9	3.0	2.9	2.9	2.9	2.9
SS-30	2.9	2.9	2.9	2.9	2.9	2.9

Table 31

Design Thickness, inches:

$$E_s = 30,000 \text{ psi}, EAL = 1 \times 10^4 \text{ MAAT} > 65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	2.5	2.5	2.5	2.5	2.5	2.5
CMS-0	2.6	2.5	2.6	2.5	2.6	2.5
CMS-7	5.8	5.2	5.8	4.8	5.7	4.8
SS-15	2.7	2.6	2.6	2.5	2.5	2.5
SS-30	2.5	2.5	2.6	2.5	2.5	2.5

Table 32

Design Thickness, inches:

$$E_s = 30,000 \text{ psi}, EAL = 1 \times 10^5 \text{ MAAT} > 65F$$

	<u>SAN BERNARDINO</u>		<u>FRESNO</u>		<u>GRANITEROCK</u>	
	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>
CSS-0	3.1	2.9	2.9	2.9	3.1	2.9
CMS-0	3.0	3.0	3.0	2.9	3.0	2.9
CMS-7	6.1	5.2	6.0	4.8	5.8	4.8
SS-15	2.9	3.0	2.9	2.9	2.9	2.9
SS-30	2.9	2.9	2.9	2.9	2.9	2.9